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MONOGRAPH ON

Corrosion Tests and Materials of Construction

FOR

Chemical Engineering Apparatus

By

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AND

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PREFACE

The American Institute of Chemical Engineers, in issuing this monograph on the subject of materials of construction and their resistance to corrosion, well realizes that but a fraction of the information known about this vast subject is included therein. Much of this information is scattered in the literature, still more is locked in the files of the research laboratories of the chemical industry. Since the two papers which constitute this book, and the discussion which they called forth, seemed to collect so much of this information in a readily accessible form, the American Institute of Chemical Engineers felt it advisable to make the matter still more accessible to design engineers by issuing it separate from the Transactions of the Institute.

The duPont Company has been very generous in releasing this information for publication. It is hoped that their example, through this monograph, will stimulate other companies to release like information. If sufficient such information is brought to the attention of the American Institute of Chemical Engineers, and if the popularity of this monograph warrants it, an enlarged and corrected edition will later be brought out.

It is hoped, also, from time to time, to issue other additional monographs in this series, to contain data useful to the designer of chemical equipment and plant.

FRED C. ZEISBERG,
Chairman, Committee on Publication.

AUG. 1, 1923.

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LABORATORY CORROSION TESTS

By W. S. CALCOTT and J. C. WHETZEL

Jackson Laboratory, E. I. duPont de Nemours & Co., Wilmington, Del.

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The author expresses his appreciation of the permission accorded him by E. I. duPont de Nemours & Co. to publish the data included in his paper, much of which was collected when he was a member of that organization.

H. F. WHITTAKER.

LABORATORY CORROSION TESTS

By W. S. CALCOTT and J. C. WHETZEL

Read and discussed at the Wilmington Meeting, June 22, 1923

Introduction

Difficulties in chemical manufacturing are due not solely to the actual chemical process, but often to the difficulty of finding materials of construction of sufficient resistance to withstand the chemical and physical stresses of the operations and also prevent contamination of the product. The chemical resistance of a metal or its ability to withstand corrosion is, therefore, an important problem of chemical manufacture.

For the purposes of this report, corrosion of a metal may be defined as the reaction between the metal and another chemical compound by which a metallic product is formed which, possessing no mechanical strength, decreases the usefulness of the metal. The metallic compound may remain attached to the original metal as a coating or may be entirely removed from the metal, the result being the same in either case—a reduction in the amount of material of useful mechanical properties. Natural corrosion is the reaction between a metal and water. Chemical corrosion may be considered as including the reaction between the metal and a corrosive agent existing at any particular concentration. The mechanism is essentially the same in both cases. The present report is concerned with chemical corrosion solely.

Chemical corrosion data are of the greatest importance. Ability to make a proper choice of material for use in plant apparatus will often determine the success of an operation. These data must be not only qualitative, but also quantitative. It is not sufficient to know that one material will withstand the action of a given mixture better than another, but the comparative rates of deterioration must be known in order that the increased initial cost of one material may be balanced against the higher depreciation cost of another. In order to obtain these data, standardized methods of testing must be employed, together with intelligent application of the results to plant practice. Conditions within the plant must be observed in order that these may be duplicated in the laboratory. Such standard methods as have been adopted are included in the present report. If exact information is

available as to composition of the corrosive agent, concentration and temperature variations, impurities and movement of liquid within the apparatus, it is easily possible to determine the best metal for use before starting an operation, and thus predict not only the financial gain through decreased deterioration costs, but also the gain through the use of apparatus which will stand up and give continuous operation. Such information may also possibly determine the ultimate success or failure of a process.

The present report contains, in addition to methods of testing and interpretation of data, a discussion of the theory of corrosion. A bibliography of chemical corrosion, indexed in such a manner that it may be readily used as problems are encountered, and tabulations and summaries of the data on corrosion available at this laboratory are included.

Summary

I. The tendency for corrosion of a metal by a solution depends upon (1) the potential effective for corrosion as determined by the combination of metal potential, overvoltage, and concentrations of metal and corroding ion; (2) the resistance offered by a protective coat; and (3) depolarization reactions removing hydrogen and protective products of corrosion.

II. The rate of the corrosion reaction varies as (1) area of metal computed from its linear dimensions, (2) rate of diffusion in corroding liquid, (3) saturation concentration of metal in corroding liquid, and (4) movement or velocity of corroding liquid. For a given set of conditions, the rate is constant in most laboratory experiments only after an initial time period (48 hrs.) has elapsed. The rate is increased greatly by increase in temperature, the logarithm of the rate varying as a straight-line function of the temperature for the range encountered in practice (20°–100° C.). More strictly, the logarithm of the corrosion rate is inversely proportional to the absolute temperature, as expressed by the following equation

$$\log R = A + \frac{B}{T},$$

where A and B are constants, R the rate of corrosion, and T the

absolute temperature. The simpler relation is, however, convenient for ordinary use.

III. A standard immersion corrosion test has been established for determining the rate of corrosion in solutions at rest expressed as inches penetration per month. All known factors affecting the results are described. A test for use with moving solutions, a review of electrochemical, microscopic, indicator, and vapor corrosion methods are contained in a discussion of corrosion measurement.

IV. Complete tabulations of corrosion data on file at this laboratory, a few extracts from the literature and a bibliography of chemical corrosion, arranged for use as specific problems arise, are attached.

V. The information necessary for determination of corrosion data and for its application to plant practice is listed and discussed. A brief outline of the use of materials against specific substances and for certain chemical operations is included. Methods of corrosion prevention are discussed in a general way.

I. Theory of Corrosion

A. Tendency of Corrosion Reaction

The driving forces of corrosion are almost entirely electrochemical, the electrochemical theory for natural corrosion having been generally accepted in this country. The fundamental requirement for corrosion is the presence of a solvent. If a solvent is present, the intensity of the action may be either great or small. The degree may be predicted to some extent by applying the general principles of electrolytic reactions.

Corrosion may be represented by an ionic reaction of the following type:

$$M + \overset{+}{H} = \overset{+}{M} + H.$$

The electrically neutral atom, M, interacts with the hydrogen ion, $\overset{+}{H}$, with the resultant production of a metal ion, $\overset{+}{M}$, which has taken up the hydrogen's electrical charge, depositing the latter as free hydrogen, H, on the surface of the metal. The type of reaction just described is the characteristic one for all cases of acid corrosion, which is by far the most important in chemical works. Of the cor-

rosion tests on file at this laboratory, about ninety-five per cent are concerned with acid corrosion. The remainder are chiefly basic, in which the metal forms an anion with an atom of oxygen, while hydrogen is liberated as before.

$$M + \overline{OH} = \overline{OM} + H$$

In any case, the metal goes into solution positively charged, resulting in the production of an electrostatic charge on the metal, preventing any appreciable corrosion unless this is neutralized through the formation of a complete voltaic cell, by flow of current through an external circuit. The latter may, however, be composed of two points of different potential on the metal itself caused by the non-homogeneous character of the surface.

The reversibility of the corrosion reaction is controlled by four primary terms composing it. In order to simplify the theoretical discussions, the acid reaction will be taken as the type, although the mechanism is essentially the same with any other. In the following restatement of the reaction, the determining factors are indicated under each component:

$$\underset{\text{I. Protective Coat.}}{M} \quad + \quad \underset{\text{III. Hydrogen Ion Concentration}}{\overset{+}{H}} =$$

II. Metal Potential.

$$\underset{\text{IV. Metal Ion Concentration.}}{\overset{+}{M}} \quad + \quad \underset{\text{V. Overvoltage. VI. Depolarization.}}{H}$$

These six factors determine the tendency for metal corrosion. In some cases, one factor may be so important that the rest are rendered negligible. This is true, however, of many common phenomena and should not be used as an argument against theoretical discussions of the corrosion reaction.

1. *Protective Coat.*—A coherent impervious film of an insoluble compound formed on the metal during the corrosion reaction will prevent perfect contact between the solution and metal, thus essentially removing the latter from the sphere of action. In order to prevent corrosion entirely, the film must be very dense and coherent. Often the protective film is an oxide, but all insoluble oxides formed

during the reaction are not necessarily protective. Porous iron rust will not protect against even atmospheric corrosion, but, by catalyzing the hydrogen removal, actually accelerates corrosion. Magnetic iron oxide will protect if it be continuous over the surface, but, if the metal is exposed, accelerates the reaction, since this oxide is electro-positive to iron. Aluminum is protected even against some of the strongest acids by its coat of oxide or basic compound.

The production of a protective coat may be developed into an important preventative of corrosion. By the addition of 0.05 to 0.25 per cent copper to the ladle before pouring steel, a metal resistant to acids is obtained, possibly through the formation of a protective oxide of copper. If sulphate ion is added to an acetic acid solution, the corrosive action against lead is lessened. A protective coat may also be formed through the differential corrosion of a metal, by which the material resistant to corrosion accumulates on the surface as corrosion proceeds, thus preserving the underlying metal.

The efficiency of a protective film or coat is determined largely by the concentration, temperature, and movement of the corroding liquid. In all cases the corrosion is increased as the solubility or removal of the protective coat is accelerated. A high concentration of sulphuric acid will dissolve lead sulphate, thus exposing metallic lead to corrosion, which will not occur at lower concentrations where the lead compound is insoluble. With aluminum the solubility of the coat, and consequently the corrosion, decreases with increasing concentration. Seligman and Williams [1] showed that the corrosion of aluminum by fatty acids reaches a minimum just before the water is entirely removed. When the anhydrous state is reached, the corrosion increases enormously. Water appears to be essential for the formation of the protective coat in this case. Increase in the temperature in general causes the removal of the protective film by solution. The concentration and temperature effects may usually be predicted by a consideration of the chemical character of the coating. If the liquid possesses considerable velocity across the metal surface, the protective coat is likely to be torn off mechanically, or its precipitation on the metal more or less prevented by rapid removal of the solution in contact.

2. *Metal Potential.*—The electrolytic potential or solution tension of the metal determines its affinity for the charged atom or ion pro-

[1] *J. Soc. Chem. Ind., 35,* 88 (1916).

ducing corrosion, and therefore is an important factor in determining its tendency to go in solution. Everything else being equal, for a homogeneous metal, the relative potential between the metal and solution would determine the corrosion rate. As a matter of fact, a homogeneous metal is never obtained in practice, and electrolytic action on the metal surface between points of different potential and the other corrosion factors are often of such importance that the potential may be neglected.

Gore [2] determined the relation between the voltaic current produced through an external circuit and the amount of corrosion. He found the weight of metal equivalent to the current produced varied from a few per cent to almost a hundred per cent of the total corrosion. The excess corrosion is caused by internal currents set up between electrodes formed on different parts of the metal surface itself. These differences exist upon nearly every surface, owing to the non-homogeneous chemical or physical character of the metal. The components of alloys will corrode differentially. A common example is the dezincification of brass. The selective corrosion of the iron-carbon alloys of steel has been noted often. The intergranular cement also corrodes in some cases more rapidly than the crystallized structure.[3] It is undoubtedly possible by simple surface treatments, such as cementation and case hardening, to produce steels resistant to corrosion in varying degrees. Stresses,[4] variations in structure by heat treatment,[5] and other purely physical effects will change the metal potential at points, resulting in the production of current. Although the potentials in these cases are very low, a large current flow with equivalent large corrosion will result because of the low resistance of the circuit. These anodic and cathodic points have been demonstrated by Walker and Cushman with indicators.

The normal value of a metal potential may be overcome by the production of the potentials in the circuit. Thus the important overvoltage effect after electrochemical action begins is equivalent to a lowering of the solution tension of the metal. The mechanism of passivity of metals is not entirely known, but the result is really the same as if the potential of the metal had been lowered. Corrosion by stray electric currents through the impression of an external elec-

[2] *Proc. Roy. Soc. London, 36,* 331 (1883).
[3] Ruder, *J. Ind. Eng. Chem., 5,* 452 (1913).
[4] Walker and Dill, *Trans. Am. Electrochem. Soc., 11,* 153 (1907).
[5] Eastick, *Metal. Ind., 11,* 524.

tromotive force is equivalent to a change in the solution pressure. Contact between two dissimilar metals will produce accelerated corrosion in an electrolyte.

Electrolytic corrosion is of special importance in chemical works. The intensity of the corrosion depends primarily upon the resistance in the external circuit and electrolyte. A very high corrosion over a broad area will result if the two metals are immersed in strong electrolytes of low resistance such as are encountered in chemical plants. Although the effective metal potential always determines the direction of electrolytic action between metals, it does not determine the real corrosion. Thus iron may be protected at the expense of zinc, but aluminum, although more electro-positive, does not protect because of its oxide coat, which renders it substantially inert.

An external electromotive force is not necessarily applied in such a direction as to increase the corrosion, but may be applied to its prevention by lowering the metal potential. This may be done either electrochemically by making electrical contact with a metal of higher potential or by making the metal to be protected the cathode through a direct current generator.[6]

Difference of potential of metals against solutions can not be determined absolutely, as a potential will exist at the other point of connection to the solution. By the use of standard normal electrodes fixing the concentration of metal ion in the solution relative values may be obtained. The series for the common metals against the normal hydrogen electrode ($H = 1$ mol liter, $P_{H_2} = 1$ atm.) in a solution containing one mol. of metal ion per liter is given below:[7]

Metal	Ion	Potential volts
Aluminum	Al^{+++}	+1.28
Zinc	Zn^{++}	+0.76
Iron	Fe^{++}	+0.43
Lead	Pb^{++}	+0.12
Tin	Sn^{++}	+0.1
(Hydrogen)	$(H)^{+}$	(0.0)
Copper	Cu^{++}	−0.34
Silver	Ag^{+}	−0.79
Gold	Au^{+++}	−1.1

[6] Gee, *J. Soc. Chem. Ind., 32,* 521 (1913).

[7] Nernst, "Theoretical Chemistry," p. 806 (4th Eng. edition), and others.

Alloys show against a solution the potential of the less noble phase.[8] Some metallic compounds show potentials differing little from those of pure metals.

The tendency for solution is very great with metals high on the list and correspondingly low for those farther down. These relative values are, of course, influenced by the hydrogen and metal ion concentrations and may be completely overcome by the overvoltage.

3. *Hydrogen Ion Concentration.*—The effective potential producing corrosion is affected only by enormous changes in the hydrogen ion concentration. In most cases occurring in practice, sufficient change is not produced sensibly to affect the tendency for solution, caused by the metal potential. Thus, from the relation between electrical and chemical energy, the dependence of potential on concentration is given[9] by:

$$E = \frac{NRT}{F} \ln \frac{C_1}{C_2},$$

or at ordinary temperature (25° C.) for hydrogen

$$E = 0.059 \log \frac{C_1}{C_2},$$

in which E represents the difference in potential in going from concentrations C_1 to C_2. Experimentally the range of hydrogen ion concentration has been shown to be from 10 molal in strong acid to 10^{-15} in strong alkali, making it possible to obtain a difference of about one volt. Since the relative potential of iron is only 0.6 volt, it is thus possible entirely to prevent its corrosion by the use of an alkaline solution. If the water in steam boilers is kept 0.03 normal with alkali, corrosion is entirely inhibited.

It has been demonstrated by Acree,[10] and others, that the addition of neutral salts gives a slight increase in the ionization of weak acids. The effect is so small, as shown by the logarithmic term, that the influence on corrosion is negligible. The enormous changes in hydrogen ion concentration, required for electrochemical effects, must not be confused with the important effect of concentration changes in the

[8] Bancroft, *Trans. Am. Electrochem. Soc., 3,* 297 (1903).
[9] Noyes and Sherrill, "General Principles of Chemistry."
[10] *Am. Chem. J., 41,* 457 (1909).

corroding liquid on the solubility of the products of corrosion, especially protective coats. Electrochemical considerations give tendencies, but whether the reaction will take place appreciably is determined by purely chemical factors.

4. *Metal Ion Concentration.*—The influence of the metal ion concentration is relatively unimportant and usually negligible in its effect on the solution tension of the metal in problems of corrosion. This concentration influences the metal potential according to the same function by which the hydrogen ion influences the potential of the hydrogen electrode. If the variations are of a very large order of magnitude, marked effects are produced as before. Thus iron will not displace copper in cyanide solution because of the low concentration of copper ion ($\overset{+}{Cu} = 10^{-19}$). Zinc may be plated out on one end of a zinc rod, immersed in saturated zinc chloride solution, while zinc will dissolve at the other end, immersed in water in contact with the chloride solution. These effects are caused directly by enormous differences in concentration of the metal ion.

5. *Overvoltage.*—No appreciable corrosion will take place without flow of current either between points of different potential on the metal surface or through an external circuit. As soon as the current begins to flow, a back electromotive force appears, thus reducing the potential effective for corrosion. This back electromotive force will continue to increase with resultant decrease in current flow until finally a decreased permanent current is obtained or electrochemical action stops almost entirely. This excess back electromotive force measured against the hydrogen electrode is the overvoltage, provided other disturbing factors are eliminated. In this case with hydrogen, the cathodic overvoltage is obtained. If oxygen is evolved at an anode, the anodic overvoltage is obtained. The overvoltage potential is a measure of the energy required to set free hydrogen after it has been deposited on or in the metal electrode.

From the data of Newbery,[11] the more common metals may be arranged in the order of their cathodic overvoltages in sulphuric acid as follows:

[11] *Mem. Proc. Manchester Lit. Phil. Soc., 61,* Parts II, III, Mem. No. 9, *C. A., 12,* 2496.

Metal	Cathodic Overvoltage, H_2 in H_2SO_4 Solution
Zinc	0.75 volt
Tin	0.49
Lead	0.42
Gold	0.36
Copper	0.33
Silver	0.29
Iron	0.27
Aluminum	0.19
Nickel	0.24
Platinum	0.17

The higher the metal in the table, the more difficult it becomes to deposit hydrogen. Since hydrogen must be deposited before corrosion takes place, the higher the metal occurs in this list, the more resistance overvoltage offers to its corrosion.

Several striking illustrations are given above of the necessity of considering all the factors affecting corrosion. Zinc has a higher overvoltage than iron, but electrolytic action with the two in contact will result in corrosion of the zinc, since the actual combination with metal potentials in such a cell is sufficient to overbalance the high overvoltage of zinc. The zinc overvoltage makes itself felt at low hydrogen ion concentrations, thus zinc is not subject to atmospheric corrosion, although its metal potential is much higher than that of iron. For minimum corrosion the overvoltage should be high and the negative potential of the metal low.

Theoretically a metal will dissolve in acid only if the sum of its single potential and overvoltage is less than the single potential of a hydrogen electrode. Hadfield and Newbery [12] have made use of measurements of these quantities in predicting corrosion of steel. The methods of testing are complicated and slight errors will change entirely the order of corrosion, since the difference of two quantities of nearly the same magnitude is often considered.

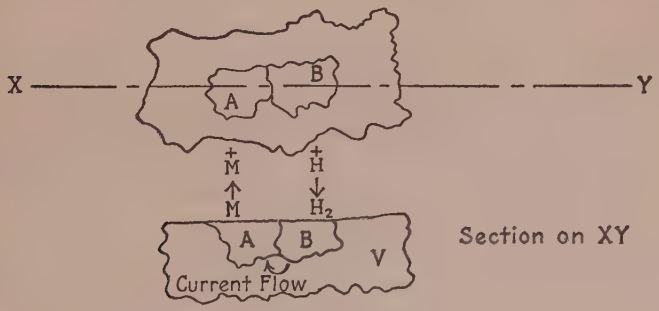
In addition to overvoltage at a point of gas evolution, an overvoltage effect is possible at any point where a change from ion to metal takes place. Measurements have been made of this potential. It is significant that the metal overvoltages are highest with nickel, iron, and cobalt. As these are also the metals most easily rendered passive, passivity may be related to a high metal overvoltage caused by rapid change from ion to metal.

[12] *Proc. Roy. Soc. London,* A93, 56 (1917); *C. A., 11,* 1814.

6. *Depolarization.*—The rapid removal of the products of corrosion, especially the deposited hydrogen, results in greatly accelerated corrosion. Any oxidizing agent will accelerate corrosion by removal of hydrogen through its oxidation to water. This type of depolarization is catalyzed also by the solid present; the metals of the iron group are catalysts. Catalytic action apparently varies inversely as the overvoltage. Zinc does not catalyze the removal reaction at all, which, with the difficulty of depositing due to overvoltage, prevents corrosion under ordinary conditions notwithstanding its high potential. Polarization is decreased by increase in temperature and rapid movement of the solution across the metal surface. It is also quite probable that corrosion is somewhat accelerated in a vacuum vessel because of the more rapid removal of hydrogen. However, the indications are that this vacuum effect is so slight as to be almost negligible (see data under velocity-corrosion effect).

Summary

From the preceding discussions of the factors affecting the tendency for corrosion to take place, the conditions may be visualized and the effect of each factor more definitely established. If *A* and *B*



two points of different potential upon a metal surface, *A* being electro-negative to *B* and hence the anode, the *metal* (*M*) will dissolve at *A*, with the metal *ion* (M^+) passing into the main body of the solution unless an insoluble compound is formed by combination with an ion from the solution, in which case corrosion will be hindered or entirely prevented as soon as the *protective coat* becomes sufficiently

dense. The formation of M^+ with flow of current necessitates the deposition of the *hydrogen ion* (H^+) on the cathodic surface with formation of free hydrogen. If the metal surface is such as to produce a high *overvoltage* effect, the reaction will gradually decrease in intensity until the overvoltage potential reaches its equilibrium value. If the overvoltage is sufficiently high, corrosion may be practically stopped. In any case the effective potential, neglecting the effect of M^+ and H^+ concentrations on their respective electrodes, will be equal to the algebraic sum of the metal potential against the solution and the overvoltage. The removal of hydrogen or metallic products by *depolarization* with oxidizing or other agents will increase the rate of corrosion.

The conditions represented here may only last for a short period with a subsequent change of polarity due to the entire removal of the material acting as points of different potential, the uncovering of other material, or to the effect of the corrosion products. These reversals of polarity have been demonstrated by Cushman [13] and others with indicators.

Electrolytic considerations indicate the tendency for corrosion, but do not take into account many factors affecting the rate of the reaction, which is discussed in the section following.

B. Rate of the Corrosion Reaction

1. *Diffusion Theory.*—Although a study of the rate of the corrosion reaction is complicated by initial electrochemical effects, disturbance due to gas evolution, and protective coat formation, a consideration from the viewpoint of rate of reaction in heterogeneous systems [14, 15] gives much valuable information.

Nernst [16] formulated from the work of Noyes and Whitney [17] the generalization that at the boundary between two phases, equilibrium is established with a practically infinite velocity compared with the rate of diffusion into or out of the saturated boundary layer.

[13] Cushman and Gardner, "Corrosion and Preservation of Iron and Steel."

[14] Nernst, "Theoretical Chemistry," p. 619 (4th Eng. edition).

[15] Lewis, "A System of Physical Chemistry. I. Kinetic Theory," p. 444 (2d ed.).

[16] *Z. Phys. Chem., 47,* 52 (1904).

[17] *Z. Phys. Chem., 23,* 689 (1897).

Thus, for the case of a metal and a liquid, if

w = weight of metal corroded in time, t,
w_1 = weight of metal in saturated layer of liquid at surface of metal,
w_2 = weight of metal in main body of solution,
v_1 = volume of saturated layer of liquid,
v_2 = volume of main body of solution,
c_1 = concentration of metal in saturated layer of solution,
c_2 = concentration of metal in main body of solution,

then the rate of corrosion, $dw/dt = k(c_1 - c_2)$, in which k is a velocity constant for the corrosion reaction.
Since,

$$c_1 = \frac{w - c_2 v_2}{v_1}$$

$$\frac{dw}{dt} = k\left(\frac{w - c_2 v_2}{v_1} - c_2\right) = k\left(\frac{w - c_2(v_2 + v_1)}{v_1}\right) \qquad (1)$$

Brunner [18] determined the thickness of film for several cases analogous to corrosion, the value remaining remarkably constant, averaging about 0.03 millimeter. For the volume of solution encountered in corrosion work, it can be readily shown that v_1 is negligible in comparison with v_2 for a thickness of saturated film of the order of magnitude of 0.1 millimeter, or sensibly $v_2 = v_2 + v_1$,
substituting in equation (1)

$$\frac{dw}{dt} = k\left(\frac{w - c_2 v_2}{v_1}\right)$$

But since $c_1 v_1 = w - c_2 v_2$,

$$\frac{dw}{dt} = k\, c_1 \qquad (2)$$

This result would have followed directly if c_2 were assumed negligible in comparison with c_1, but this is not apparent at first sight. It is also in accordance with Wilhelmy's law, which states that the velocity of a reaction is proportional to the concentration of reacting substance.
Now, if A = area of metal exposed to corroding solution,

D = diffusion coefficient of corroding solution, expressed in quantity of substance, which, during unit time, will

[18] *Z. physik. Chem.*, *47*, 56 (1904).

pass through unit sectional area, the concentration gradient being unity,

S = thickness of saturated layer.

Then applying Nernst's theory of heterogeneous reaction velocity as experimentally confirmed by Brunner and others, the rate of corrosion may be expressed

$$\frac{dw}{dt} = \frac{AD}{S}(c_1 - c_2)$$

from which

$$k = \frac{AD}{S}$$

Equation (2) may now be rewritten

$$\frac{dw}{dt} = \frac{AD}{S} c_1$$

For any metal corroding in a given solution, c_1 is a constant determined by the equilibrium between the metal and solution. Thus, integrating,

$$w = \frac{AD}{S} c_1 t$$

the constant of integration dropping out, since $w = o$ when $t = o$.

Thus the corrosion will vary directly as the area of metal, diffusion coefficient of the solution, saturation concentration of the metal in solution and the time, and inversely as the thickness of the saturated layer. Brunner,[19] van Name and Edgar,[20] and Nernst and Merriam [21] have shown that the thickness of the saturated film depends upon the velocity of stirring the main body of the solution. Using an efficient paddle stirrer, they found the thickness to vary inversely as the 0.6 to 0.9 power of the rate of stirring. The indications from this data are that the corrosion will vary directly as a low power of the velocity. With metals and strong electrolytes, the power will probably be higher than with the dilute solutions used by these investigators, the protec-

[19] *Z. physik. Chem., 47,* 56 (1904).
[20] *Z. physik. Chem., 73,* 97 (1910).
[21] *Z. physik. Chem., 53,* 235 (1905).

tion afforded by protective coats and overvoltage probably decreasing greatly at high velocities.

It should be possible to demonstrate the dependence of the rate of corrosion upon the diffusion constant (D) of the solution and solubility (c) of the salt in the solution by proper choice of conditions. In one case, a metal must be exposed to the action of a pair of solutions, probably acids, both having the same ionization and same solubility for the metallic salt, but with diffusion constants differing as widely as possible. For another test, a metal and pair of solutions must be chosen so that the identical conditions are obtained for everything except the solubility, which should vary as much as possible. If such sets of conditions can be secured, considerable valuable information could be obtained upon the rate of the corrosion reaction by carrying on the parallel tests.

The value of the area, A, is not the true microscopic surface of the metal, but the value of the film area which is sensibly equivalent to the "quadratic dimensions." For this reason, very fine polishing is of little use in preparing test specimens for corrosion determinations.

2. *Concentration Effect.*—The effect of concentration of the corroding solution upon rate of corrosion is indicated in Table I and Figs. 1–5, Appendix, for simple aqueous solutions and for mixed solutions. The rate varies with the solubility of the metal or the product of corrosion in the solution. If the solvent producing solution is known and its concentration is plotted against the rate, a straight line should be obtained as indicated by preceding equation (2). The fact that the rate of corrosion of aluminum by strong nitric acid varies approximately as a straight line function of the water content of the acid has been demonstrated by Seligman and Williams.[22]

The peculiar effect of increase in corrosion rate of metals corroding in acid solution, by the addition of a salt of the metal to the acid, has been noted in this laboratory and by other observers. A slight increase in acid ionization with resultant higher hydrogen ion concentration, such as occurs with some acids under these conditions, can not account for this effect; a hydrogen ion concentration of a different order of magnitude must be produced in order sensibly to affect the electrode potential. A possible explanation exists in the

[22] *J. Soc. Chem. Ind., 35,* 665 (1916).

higher concentration of the products of reaction in the surface film, because of the additional solubility produced by a higher concentration of metal salt, or the removal of a protective coat by solubility in the salt solution. It is a fact that many metallic hydroxides are peptized and passed into colloidal solution in metallic salt solution. Although this increased corrosion rate is of great importance in considering the specific case of corrosion in acid solution containing metallic salts, it need not be considered ordinarily in corrosion work with ordinary acid solutions in the plant, since the main volume of the solution is sufficient to neglect concentration changes due to the progress of the corrosion reaction. However, a sufficiently high concentration of metallic salt may be produced in small pockets so that corrosion is seriously increased. For example, aluminum still heads, resistant to corrosion by acetic acid alone, are corroded rapidly if small pockets exist and an appreciable concentration of aluminum salt is allowed to collect over long periods.[23]

In the laboratory, the volume of test solutions must be made sufficient to prevent concentration changes due to the progress of the corrosion reaction.

Impurities in solution also have a great effect upon corrosion, undoubtedly due to their influence upon the saturation concentration of the reaction products. The influence of salts in acid solutions may usually be predicted by a consideration of the acid generated by interaction. Thus the addition of common salt to a sulphuric acid solution, with the formation of hydrochloric acid, produces far greater corrosion of lead, while the addition of a small amount of sodium sulphate to acetic acid decreases the rate of lead corrosion.

3. *Time Effect.*—The time required for initial effects to subside and the rate to become constant is indicated by the curves of Figs. 6 and 7, Appendix, which show the tendency for three different cases of corrosion. Evidently corrosion measurements for long time extrapolation should not be made until after this initial period. The error in three of the four cases due to averaging the rate from zero time to the time indicated in the plot is shown in Fig. 8, Appendix. For these three cases studied, an approximately true value of the rate may be obtained by measuring it between forty-eight and ninety-six hours. For the fourth case, aluminum in nitric acid, corrosion is

[23] Seligman and Williams, *J. Soc. Chem. Ind., 35,* 88 (1916); *36,* 409 (1917).

directly proportional to the time from the start. Thus, simple measurement from zero to forty-eight or ninety-six hours may give results 100 and 20 per cent high respectively. Although this initial time period of forty-eight hours has been established from only three sets of data, it is probable that these represent the maximum, and that in other instances a shorter time will be sufficient. Additional work should be carried out on this subject with more refinements, especially in regard to accurate temperature control.

If the product of corrosion must undergo a measurably slow reaction to be removed, diffusion alone will not determine the rate. If the main resistance is due to diffusion, increased movement of the liquid will increase the rate, but if the reaction at the metal boundary proceeds slowly, increased movement will have little effect. In any event, a theory which does not consider diffusion is incomplete.

4. *Temperature Effect.*—Temperature affects the rate of corrosion as well as the electrochemical tendencies for it to take place. For many homogeneous reactions the velocity is doubled for each 10° rise in temperature. With many heterogeneous reactions, where the rate is determined by diffusion, the velocity is increased about 1.5 times for the same rise. Temperature increases D, the diffusion coefficient, by lowering the viscosity of the solution. The smaller the initial diffusion rate, the greater the temperature coefficient. Thus hydrochloric and acetic acids have values of the diffusion coefficient [24] of 2.3 and 0.7 respectively for 4N acid, expressed in grams per day diffused through an area of one square centimeter down a concentration gradient of one gram per centimeter. The fractional increase for each ten degrees rise is 0.19 for hydrochloric and 0.28 for acetic acid.

Equations representing the increase in rate of reaction with temperature are largely empirical with little theoretical base. Arrhenius [25] and others have given such equations for the change of velocity constant of homogeneous reactions with absolute temperature, but none have been attempted for a reaction of the corrosion type. One article [26] was discovered in the literature in which the logarithm of the corrosion rate had been plotted against the temperature in order to make the low temperature rate appreciable on the diagram. Throughout a wide range the data followed approximately a straight line.

[24] Landolt Börnstein—Tabellen, 4th ed., p. 133.
[25] *Z. physik. Chem., 4,* 226 (1889).
[26] *J. Soc. Chem. Ind., 35,* 665 (1916).

No attempt was made to interpret this, although the relation is obvious. This relation has been found to hold in general, and makes a useful empirical rule, on account of the ease of plotting the data. The standard equation for the variation in the velocity of homogeneous reactions, namely,

$$\text{Log } R = A + \frac{B}{T},$$

has been found to hold also for the heterogeneous corrosion type of reaction. This equation, though less convenient to use, rests on a theoretical foundation, and can be used safely for extrapolation within reasonable limits.

C. *Vapor Corrosion*

When corrosive vapors react with metals, the products of corrosion are not ordinarily removed. Even if no really protective coat is formed, the products will accumulate, covering the surface and increasing the difficulty with which the vapor can reach the metal, thus lowering the corrosion rate with time. For this reason, all vapor tests made so far are more or less unreliable for long time extrapolation, but the results are comparable, indicating in a general way the best material for use.

A study of the reaction rate at different time intervals would give data by which the rate could be calculated at any given time and the corrosion predicted closely.

II. Corrosion Measurement

The general method usually employed for determining the rate of corrosion of materials consists in exposing specimens of the material to the action of the corrosive agent for a definite time and determining the loss in weight per unit area. No one has apparently tried to standardize a test of this type by measuring the influence of the numerous factors. An attempt has been made recently at this laboratory, and although many of the points need additional confirmation, it is felt that the methods described will give reasonable accuracy in the majority of cases.

A. *Standard Corrosion Test with Solutions at Rest*

Metal Test Piece.—Size, 2″ x 1″ x 0.1″ (area = 4.6 sq. in.). Dimensions should be accurate to 0.01 inch in order to save time of

measurement and area calculation in the laboratory. Other shapes may be used within a range of ratio of length of edge to total area of test piece between 4 and 8. (See Table V, Appendix, for shape effect.)

Preparation.—The strip of indicated size may be cut from flat sheet metal or turned from pipe. Remove tool marks by successive use of file and emery. Exceedingly fine finishes are unnecessary, but the surface should be clean and reasonably smooth.

Corroding Solution. Volume.—Use 250 cubic centimeters per test piece of given area (4.6 sq. in.) for fairly rapid corrosion rate (0.01 inch penetration per month). The volume should be increased in proportion for pieces of greater area.

Procedure.—Place corroding solution in flask or wide mouth bottle and bring to temperature of test. Regulate this temperature to at least 1° C. in some type of rough thermostat. Suspend the weighed test piece upon a glass hook from a stopper of size to fit flask or bottle loosely and unaffected by corroding solution. Immerse test piece in solution when it reaches the proper temperature, closing the bottle or flask with the stopper. If the test is being made at a high temperature, a reflux condenser must be used, taking care to prevent condensate running directly on the test piece.

If the highest accuracy is required, expose one test piece for approximately forty-eight (48) hours and another for approximately ninety-six (96) hours. Remove from solution, wash thoroughly in a stream of water, and remove any coating. This cleaning may be done by dissolving off the coating (lead sulphate in ammonium acetate solution, lead chloride in hot water, etc.) or by rubbing and scouring with or without a soft powder as a mild abrasive. Do not adopt any method of cleaning until the error due to its use has been determined. Reweigh test piece after thoroughly drying, especially wiping out the hole by which it was suspended on the glass hook. From the loss during the last forty-eight hours, obtained by the difference in weight of the two test pieces, calculate the average rate of corrosion ($t = 48$ hrs.) as indicated under calculations.

Relatively good accuracy (results will be 20 per cent $\pm$ high) may be obtained in most cases by omitting the first measurement and averaging the rate over the entire period from zero to ninety-six hours. (See Fig. 8, Appendix.) The method to be used in any given test will depend upon the importance of the problem. Where

absolute quantitative data are necessary in balancing costs, the double determination should be made.

Run a check test simultaneously. Never place test pieces of different metals in the same container. It is permissible to place two pieces of the same metal in the same container, but they should not be in contact.

In case the metal develops pitting, this factor must be included in the results, since failure in any case will occur when a pit has entirely penetrated the metal. Determine the magnitude of this effect by grinding down on a metallographic grinding set until all the pits have just disappeared and solid metal is reached. The loss in weight during this grinding is determined and the pitting calculated as indicated.

Calculations.—

If $w =$ loss in weight in grams of test piece during immersion,
$A =$ area of test piece in square inches,
$s =$ density of metal in grams per cubic centimeter,
$t =$ time of exposure in hours,

then $C =$ rate of chemical corrosion expressed as inches penetration per month,

$$\frac{24 \times 30 \times w}{(2.54)^3 Ast} \quad \text{or} \quad C = 43.9 \frac{w}{Ast}$$

(A more logical factor for cost calculation would be expressed in pounds per square foot per year.)

In order to calculate the pitting corrosion, let $p =$ loss in weight in grams due to grinding out pits, then $D =$ rate of penetration of metal by both normal corrosion over the entire surface and local action due to pitting,

$$= 43.9 \frac{w + p}{Ast}$$

The depth of pitting or penetration due to pitting alone can not be determined from the grinding loss, but the degree of pitting may be indicated roughly by a pitting factor,[27] P.

$$P = \frac{C + D}{D}$$

[27] Aston and Burgess, *Trans. Am. Electrochem. Soc.*, *22*, 219 (1912).

In order to simplify calculations, s for the more common metals has been substituted in the preceding equations for corrosion calculation with the following results:

Metal	s	C
Aluminum	2.67	$16.45\frac{w}{At}$
Copper	8.9	$4.93\frac{w}{At}$
Iron, Cast	7.4	$5.94\frac{w}{At}$
Lead	11.4	$3.85\frac{w}{At}$
Nickel	8.8	$4.99\frac{w}{At}$
Steel	7.7	$5.71\frac{w}{At}$

Conditions and Factors Affecting Results of Tests

1. *Test Piece.*—Shape does not affect results within a reasonable range of ratio of length of edge to surface. (See Table V, Appendix.)

Fine polishing is unnecessary, although tool marks and oxide should be removed by rough treatment with emery. (See Table V, Appendix.)

2. *Volume of Corroding Solution.*—The effect of volume of corroding solution on rate of corrosion becomes practically negligible if a volume in excess of a certain minimum is used. (See Table V, Appendix.)

3. *Temperature of Corroding Solution.*—The temperature coefficient is high for all reactions, but in applying results to plant practice the works temperature would be estimated no closer than 1° C. For theoretical work in determining the law of temperature effect, it is absolutely necessary to use an accurately regulated thermostat. In comparing different metals care must be taken that the temperature is the same for all tests. (See Figs. 9 and 10 and Table IV, Appendix.)

4. *Time of Exposure of Metal to Corroding Solution.* The results of the corrosion test will vary enormously with the time of exposure. This variation is due to initial electrochemical surface

actions, such as overvoltage and to the period of time required for the formation of a protective coat. Both of these require time for reaching the equilibrium which will be maintained over a long time. Evidently initial effects of this kind must be neglected if a corrosion factor for use over a long period of time is to be obtained. The logical way is to measure the rate over an interval of time after the initial high corrosion rate has decreased and become constant. For the most careful work, this must be done. The experimental data, available at present, indicate that corrosion should be determined at the end of forty-eight and ninety-six hours. As a matter of fact, sufficient accuracy for comparative purposes may be obtained by omitting the first measurement and averaging the rate over the entire period. In the case of aluminum corroding in nitric acid, the weight of metal corroded per unit area is a straight line function of the time of exposure even for short periods. These data indicate that double determinations at different time intervals are not always necessary, but in any new case to be studied this will not be evident without testing. (See Tables II and III and Figs. 6, 7, and 8, Appendix.)

5. The magnitude of the error introduced in cleaning the test pieces is indicated for two representative cases in Table V, Appendix. This error exists only when one measurement is made; if two are made, the difference in weight neutralizes it.

B. Corrosion Test with Moving Solutions

From the consideration of saturated films, protective coats, and overvoltage effects on the metal surface, it is evident that the movement of liquid across the surface affects the protection afforded by these factors. No quantitative relationship between the velocity of solution and rate of corrosion has been determined experimentally, notwithstanding the high velocities in actual operations. In order to make determinations of this character, a glass apparatus has been constructed in this laboratory by means of which corrosive liquids may be recirculated through a tube of the material, or across a metal test piece at definite velocities.

1. *Apparatus and Method for Corrosion Test under Velocity Conditions.*—A drawing of the apparatus used in velocity corrosion tests is given in Fig. 13 of the Appendix. The circulation of the corrosive liquid through the test tube and the return for recirculation is accomplished as follows:

The corrosive liquid is drawn from one large container (K) over the metal to be tested to another (K_1) by connection of the latter with a vacuum pump. When this container is filled, the vacuum is shut off by the action of a float (F) through the air valve (A) and a slight pressure applied, thus forcing the liquid back through the large return tube (L) to the lower container (K). When the level of the liquid in the upper container (K_1) and also the float chamber (D) is sufficiently lowered, the air pressure is cut off, connection with the vacuum supply again made, and the cycle repeated. With the vacuum on, flow of liquid through the return tube (L) is prevented by a check valve (M).

The test piece for high velocities is in the form of a tube (T_1, T_2), which is inserted in the system by means of glass reducers and heavy rubber connections. By the use of two sets of tubes of different diameter, check runs may be obtained for two different velocities. Tubes of $\frac{1}{16}$" diameter are used for the highest velocity (2,000 ft./min. +). Two standard test pieces must always be placed at some point in the system to determine the static corrosion under the given conditions. This is most conveniently done by suspension on glass hooks in an overflow bottle (Q) connected to the large container by a glass syphon, the sluggishness of which prevents uncovering of the test pieces. Additional test pieces (T_3, T_4) for very low velocities (5–10 ft./min.) may be inserted in the large glass tubes on both sides of the metal test tubes. If these are inserted on the side nearest the vacuum container, they will be exposed under fairly high vacuum, which may accelerate the corrosion slightly.

Procedure.—Before insertion in the apparatus, the ends of the metal test tubes are coated with Bakelite enamel, baked on 24 hours at 100–150° C., the exposed metal surface thoroughly cleaned, and the tubes weighed. They are then ready to attach to the glass reducers by means of heavy rubber connections cut from rubber stoppers.

The metal air valve is greased, the proper quantity of corrosive liquid added to the large containers (about 20 liters), and connection made with the vacuum and air pressure supply through the screw clamps which regulate the velocity and rate of return of liquid. After the liquid begins to flow, the syphon between the float chamber and upper container is started and the flow through this regulated so that a certain lag exists in the height of liquid in the chamber, pre-

venting a stop of the float valve on dead center. The air valve must be oiled or greased every few hours. This must be done with the air pressure shut off from the apparatus or the oil will not be drawn down in the valve, but will be blown out the top by air leakage.

Since the flow over the test pieces is intermittent, the characteristic cycle of operaton must be obtained by time measurement with a stop-watch in order that the average velocity may be definitely determined. This necessitates the data indicated under *calculations*. The average time for each stop over a given number of hours is obtained by timing several representative cycles. The velocity for the given head is measured by noting the time required for a given volume to flow through a test-tube of known diameter.

Calculations.—

Let t_m = time at maximum head h.

t_0 = time at zero head during discharge.

t_a = time required to attain head, h, by rise from zero head, plus time required for decrease from h to zero.

T = total time of period to which measurements apply.

T_0 = time out for stops and shut-downs.

T_v = actual time of period to be used in average velocity calculations.

$T_v = T - T_0 t_0$.

The average head may not be obtained by averaging h directly, but h may be averaged in this manner, since the velocity is proportional to the square root of the head for the conditions encountered in this apparatus.

Thus $\sqrt{\text{Average head during time liquid flows to upper container}}$

$$= \text{Av. max. head, } h\left(\frac{t_m}{t_m + t_a}\right) + \frac{\text{av. max. head, } h}{2}\left(\frac{t_a}{t_m + t_a}\right).$$

$$\sqrt{\text{Average head during time liquid flows to upper container}} =$$

$$= \sqrt{\text{Average max. head, } h\left(\frac{2t_m + t_a}{2(t_m + t_a)}\right)}.$$

Since the square root of the average velocity head is now known, the actual head is readily obtainable. The velocity corresponding to this head is secured by noting the time required for a given volume of solution to pass through the test-tubes under the average head

maintained on the mercury manometer. If the velocity is known at about the same head, it may be obtained at the exact point by applying the square root relationship.

In the present apparatus, the lower container has been calibrated for ten liters of solution (syphon overflow bottle closed).

If m = time in minutes for drop of level of liquid, from upper to to lower 10 l (calibration work),
and d = inside diameter of tube in inches,
v = velocity through tube in ft./min.,
then =

$$= \frac{10 \times 2.2}{62.4} \frac{1}{m} \frac{4 \times 144}{3.1416 \times d_a},$$

$$v = \frac{64.5}{md^2}.$$

For example, if

$d = 1''/10$ (small metal test tube) and
$m = 8$ min.
$v = 2{,}000 +$ ft./min.
If $d = 0.9''$ (large glass tube), then for the same value of m,

$$v = 7 \text{ ft./min.}$$

After the liquid has been circulated for a few days, all test pieces are removed, cleaned, weighed, and the weight of metal corroded per unit area $(w)/(a)$ for each test piece calculated. The total time at zero velocity (t_0) is added to any time out for shutdowns (T_0), and the static corrosion taking place during this period $(T_0 + t_0)$ calculated from the rate of corrosion of the pieces under static conditions. The results for this static period, expressed in grams per square inch, are subtracted from the loss for the whole period in the same unit and the loss during the actual time $(T - T_0 - t_0)$ liquid flowed through the test-tubes is obtained in grams per square inch. Since the loss in weight over a certain time period $(T - T_0 - t_0)$, within which the known average velocity was maintained has been determined, the rate of corrosion expressed in inches penetration per month, corresponding to this velocity, may be readily calculated as in the standard test for solutions at rest.

Thus, if w_s = loss in weight during total time, T, of test piece immersed in solution at rest,

A_s = area of test piece immersed in solution at rest,

W_v = loss in weight in total time, T, of test piece subjected to moving solution,

A_v = area of test piece subjected to moving solution,

T = total time of test,

T_0 = total time out for shutdowns,

t_0 = total time that velocity across test piece is zero due to reversal of flow in apparatus,

C_v = rate of corrosion expressed in inches per month during time (T_0) when liquid is moving across surface with average velocity, v,

$$C_v = \frac{43.9}{sT_v}\left[\frac{W_v}{A_v} - \frac{W_s}{A_s}\left(\frac{T_o + t_o}{T}\right)\right].$$

An error will be introduced in the interpretation of results and in the determination of the quantitative relationship existing between velocity of liquid and corrosion by use of this intermittent apparatus. If the rate of corrosion is not proportional to the first power of the velocity, the direct averaging of velocities is not justified. The error probably will not be large, as the velocities averaged with the maximum are only correction terms. A constant flow apparatus similar in principle to the present one has been designed, but no attempt has been made to construct it. A high gravity flow tube with air lift would serve the same purpose, for solutions not affected by air.

Results should be interpreted by plotting the logarithm of the corrosion rate against the logarithm of the velocity. A straight line will be obtained if a power function exists. Very few data are available at present. The results of two runs are given below:

Velocity Average ft./min.	Rate of Corrosion min./month	Notes
1,460	0.0031	
8	0.0008	20″ vacuum
8	0.0007	atmospheric
0.1 or less	0.0007	
1,420	0.0025	
8	0.0006	20″ vacuum
8	0.0005	atmospheric
0.1 or less	0.0004	

2. *Velocity Corrosion Data.*—A number of velocity tests have already been carried out in this laboratory in the past, using methods other than those indicated. The results are indicated in Table VI, Appendix. Increase in velocity gave increased corrosion, but no definite relations were established. The following methods of testing were employed, the number used referring to the method given in the tabulation:

1. Gravity flow of solution across metal test pieces supported in glass tubes of varying diameters. Solution recirculated by air lift.

2. Test pieces attached to dish rotating in liquid.

3. Disk made of material to be tested, rotating in opposite direction to a wooden disk. Corrosion determined by cleaning and measuring thickness with micrometer.

4. Dropping liquid on metal test piece. Actually an impact test, but really gives qualitative indication of velocity effect.

C. Electrochemical Methods

1. *Metal Potential Determination.*—The single potential of a given metal against any solution may be determined by combining it with another half cell of known potential through the proper solution, and balancing the electromotive force of the entire cell against a standard cell, by means of a wire bridge and capillary electrometer. Several combinations may be necessary in order to overcome the liquid potentials. Details may be found in any work on physical chemistry.

In simple tests of the potential existing between two metals in a given solution, the electromotive force of the combination should be balanced against a potentiometer. A millivoltmeter really measures the current and the resistance of the solution may not be negligible in comparison with that of the instrument. A number of determinations with the millivoltmeter are given in Table VII, Appendix. An initial potential must not be taken as indicative of continued electrolytic corrosion. A considerable electromotive force exists initially between aluminum and iron in concentrated nitric acid, but this gradually drops until it becomes negligible as far as affecting the corrosion rate.

If free energy data are available for the chemical change involved, the metal potential may be calculated. The obsolete method of calculation from the heat of reaction should not be used except where energy data can not be obtained. Calculation from heat data as-

sumes a zero temperature coefficient for the cell combination, which may be in error by a large amount.

2. *Overvoltage Determination.*—Newberry [28] describes fully a method of measurement by which the difference in potential between a metal when liberating hydrogen or oxygen and the respective hydrogen and oxygen electrode may be obtained. A large number of determinations have been made by the same investigator.[29] Hadfield and Newbery [30] have suggested the possibility of predicting corrosion of a metal in acid solution by comparing the sum of its single potential and overvoltage with the single potential of the hydrogen electrode.

3. *Mutual Corrosion Test of Metals.*—The electrolytic corrosion of two metals in contact in a solution is measured by the current flowing between the two. By immersing the two metals in the given solution and measuring the current flow through an external circuit of low resistance containing an ammeter, a quantitative idea of the electrolytic corrosion may be obtained. The loss in weight of the metal due to electrolysis may be easily calculated from the quantity of current by Faraday's law. The current will vary with the area of the test pieces, and the distance between them; these factors must be considered when comparisons are being made. The test must be continued until initial effects have disappeared and a constant current value has been obtained. Plant conditions must be followed as closely as possible, especially with regard to temperature and movement of liquid. Hanson and Lewis [31] have made use of this method in determining atmospheric corrosion.

A test in this laboratory of the mutual corrosion of aluminum and iron by this method demonstrated that the formation of a protective coat upon the aluminum effectively prevents electrolytic corrosion. A fairly high initial current flow rapidly decreased to zero as the protective effect of the coat made itself felt.

D. Microscopic Methods

Desch,[32] Whyto,[33] and others have demonstrated the value of

[28] *J. Chem. Soc., 105,* 2420 (1914).

[29] *Proc. Roy. Soc. London, A93,* 56 (1917).

[30] *Mem. Proc. Manchester Lit. Phil. Soc., 61,* Mem. 9 (1917), C. A. *12,* 2496 (1918).

[31] *Trans. Am. Electrochem. Soc., 22,* 259 (1912).

[32] *J. Soc. Chem. Ind., 34,* 258 (1915).

[33] *J. Inst. Metals, 10,* 304 (1913); *11,* 235 (1914).

metallographic methods and the use of the microscope in indicating the mechanism of the corrosion of metals.

By examining the metal under a microscope before and after corrosion, the nature of the attack, comparative resistance of the different constituents, and texture of any adherent layers are determined. By stimulating corrosion with an externally applied electromotive force through a platinum cathode, an indication of the value of a metal may be obtained in a very short while. Application of these methods to the corrosion of brasses, by the investigators already mentioned, have given valuable results.

Metallography has been widely applied in studying the corrosion of the iron carbon alloys in steel. In fact, the ordinary methods of determining the different constituents by etching are merely selective corrosion tests. The corrosion of the intergranular cement in silicon iron alloys with exfoliation of the crystalline grains is an effect observed by Ruder.[34] In such a case, a mere immersion test would not determine the true loss in strength, since the amorphous material, giving strength to the metal, was almost entirely corroded away.

Microscopic comparison of the etching produced by the corrosive agent with that produced by standard etching solutions (alcoholic nitric acid, picric acid, etc.) will give information concerning the actual component of the metallic mass attacked. Decreased corrosion may be obtained by increasing the amount of most resistant material by heat treatment, or the addition or removal of certain constituents.

Photo-micrographs of protective metal coatings are of great value. They will determine the value of such coatings and the proper method of application. Rawdon, Grossman, and Finn [35] have applied metallography to the study of such metallic coatings, especially zinc.

The methods of preparing specimens for metallographic observations, including polishing, the use of etching solutions for determining constituents, and the technique of micro-photography, may be obtained from the numerous books on the subject.

E. Indicator Methods

1. *Color Indicators.*—Points of different potential on metal surfaces, and microscopic voltaic couples such as are formed at uncovered points on metal coated material, may be distinguished by the use of indicators which change color when brought into contact with the

[34] *J. Ind. Eng. Chem., 5,* 452 (1913).
[35] *Chem. Met. Eng., 20,* 530 (1919).

products of the anodic or cathodic reaction. The ferroxyl reagent of Walker [36] is in general use for noting the solution of iron by means of ferricyanide in acid gelatin (50 g. gelatin, 450 g. water, 1 g. $K_3Fe(CN_6)$, 1 g. H_2SO_4), especially in determining the perfection of coated iron. The addition of phenolphthalein will locate the negative pole in some solutions, since the hydroxyl ions liberated will give the characteristic pink color of this indicator. The ferroxyl indicator may also be applied to determine whether iron in contact with another metal will corrode electrolytically. A simple test with this reagent will often save a more tedious electrical test.

If need arose, it would undoubtedly be possible to devise other indicators of value for use with other metals.

2. *Precipitation and Gas Evolution.*—Zinc coated metal may be tested for the amount of coating by determining the amount of another metal precipitated from solution or the time required for the precipitation. The Preece test makes use of a copper sulphate solution. Hydrochloric acid-antimony chloride [37] and basic lead acetate [38] solutions have also been used. A summary of such methods is given in a recent article by Rawdon, Grossmann, and Finn.[39]

The fact that iron in contact with zinc will liberate hydrogen in a hot caustic solution is the basis of another test for detecting pin holes and cracks in zinc coating.[40]

F. Vapor Corrosion Methods

Vapor corrosion is determined by exposing standard test pieces to a stream of the corrosive vapor, measuring the loss in weight after removal of the coating and calculating the results as in solution tests. The method of generating the vapor will depend upon its composition, simple distillation in many cases being sufficient. If heat must be supplied for the generation, an electric hot plate should be used in order that the supply of vapor may be controlled closely. The test strips are contained in an electrically heated tube, which gives a uniform and easily regulated heat supply to prevent condensation. The temperature may be controlled with a rheostat, indications being fur-

[36] *J. Ind. Eng. Chem., 1,* 295 (1909).
[37] *J. Ind. Eng. Chem., 3,* 239 (1911).
[38] *Bull. Soc. Chim., 4,* I, 873 (Tambau).
[39] *Chem. Met. Eng., 20,* 458 (1919).
[40] *Proc. Chem. Soc. Testing Materials, 2,* 431 (1909).

nished by thermometers inserted in the tube. The details can not be fixed for all vapors, but the principle may be used.

A typical test of this character has been made with benzoic acid vapor at 250° C. on a large number of test pieces. The latter ($2'' \times 1'' \times 0.1''$) were distributed along the interior of a heated glass tube, about four feet long and 1⅛ in. in diameter, after it had been brought up to temperature by means of its electrical winding, consisting of 35′ of No. 22 Comet Resistance wire carrying about 8 amperes. After placing the strips, the vapor was turned into the tube and the test continued for about twelve hours. Vapor was supplied from a flask of boiling benzoic acid fitted with thermometer, large discharge tube, and resting upon an electric hot plate. The exit vapor from the long tube was kept at the same temperature as that of the vapor issuing from the flask. No selective corrosion in different parts of the tube was obtained.

Very little work has been done on the methods of testing vapors, but it is evident from what has already been said that the accumulation of the products of corrosion, which must take place at temperatures below that required for their volatilization, will cause a decrease in rate of attack as the time increases. No true values of the rate over long periods have been obtained, but the results are at least comparable, and will indicate the relative resistance of the metals tested.

III. Corrosion Data

A. Literature

Chemical literature contains considerable quantitative data on the corrosion of metals. In some cases the investigations have been very thorough and further work in these instances is unnecessary. For example, Seligmann and Williams have determined the action of nitric and organic acids on aluminum under practically every condition.[41] In general, all these data require calculation and rather close study before they can be applied to plant use. The labor of extracting all such data is too great for a report of this character, but the plan of making these abstracts, as definite problems arise, will be followed. For this reason a very complete bibliography (see Appendix) has been prepared with cross-references in order that the literature on a given case of corrosion may be readily available. This bibliography is intended to cover all the subject matter on chemical corrosion.

[41] *J. Soc. Chem. Ind.*, *35*, 88 (1916); *35*, 665 (1919); *36*, 409 (1917).

Additions will be made as subsequent work is produced and as better library facilities, especially on engineering subjects, become available. The aim is to produce a workable bibliography in order that long expensive testing may be saved. The corrosion of metals is essentially a problem of physical chemistry. Considerable data has been determined in this type of laboratory with great precision—far more than can be obtained in a chemical engineering laboratory. A large number of references are included on the factors affecting corrosion, especially those from the electrochemical point of view.

No attempt has been made to include all the references to natural atmospheric or water corrosion. All articles applying only to this type of corrosion have been omitted. Nevertheless, chemical and atmospheric corrosion are closely related and much subject matter of the latter type contains information of great value in chemical corrosion. For this reason, many references are included, which bear more or less directly on atmospheric and water corrosion. The same policy has been adopted with material concerning electrolytic corrosion, sea-water corrosion, corrosion in hot-water heating systems, and the prevention of corrosion. The bibliography is divided into the subheadings given below with cross-references wherever this has seemed desirable:

Chemical Corrosion of Metals
- Alloys, Special
- Alloys, Ferro
- Aluminum
- Brass
- Bronze
- Cadmium
- Chromium
- Copper
- Iron
- Iron and Steel
- Lead
- Metals, General
- Nickel
- Steel
- Tin
- Zinc
- Enamels, etc.

Corrosion Factors
- Metal Potential
- Overvoltage
- Electrolysis Solution Effect
- Rate of Corrosion Reaction

Corrosion
- General
- Tests and Methods
- Prevention
- Bibliographies

Results given in the literature are not calculated to the basis of inches penetration per month as used by this company, but data are usually available for this calculation. Conversion factors are given below for two cases already encountered. The nomenclature is the same as that used in calculations for the standard test.

Given	*Required*	*Factor—Multiply by*
Grams/sq. in. in time, t.....	in. penetration/mo.	$4.39/st$
Milligrams/100 sq. cm./24 hrs....	in. penetration/mo.	$0.000118/s$
		0.0000443 (aluminum)

B. Jackson Laboratory Files

All the data available at the Jackson Laboratory on specific cases of metal corrosion have been tabulated in Table VIII of the Appendix. A summary of data has also been prepared in Table IX, Appendix, from which the most important data for the corrosion of a metal in a given solution may be obtained without searching through the complete tabulation. Tables X, XI, and XII contain, respectively, the results of tests on corrosion by vapors, the corrosion of enamels and coatings, and the effect of immersion of different woods in dilute acid solution. The data recorded have been obtained from tests in this laboratory, and letters of information from the Eastern Laboratory and Experimental Station of this company.

Some record should also be kept of the performance of plant apparatus. Where rapid corrosion is taking place, measurement of metal thickness should be made and the results compared with laboratory tests.

IV. Application of Corrosion Data to Plant Practice

A. Information from Plant

Before a corrosion investigation is undertaken, a large sample of the corroding liquid, as it will actually exist in the plant, should be furnished unless the material is one of the common chemicals and may be secured from the laboratory chemical stock.

The following information should be furnished on a form when the request for an investigation is forwarded:

1. Type of apparatus.
2. Temperature range in apparatus.
3. Concentration changes in corroding liquid, due to both actual

changes produced during the process and those due to exposure of the atmosphere after draining.

4. Velocity of liquid in apparatus, rate of stirring, or data by which velocity may be approximated.

5. Impurities occurring in corrosive agent.

6. Cycle of operation including time of exposure of liquid per day.

7. Metals suggested from previous experience.

8. Metals which may possibly be in contact.

The influence of temperature, concentration changes, and contact with other metals has already been discussed, but little has been said concerning the effect of impurities and changes in concentration due to absorption or loss of water through exposure to the atmosphere. Small amounts of impurities will often produce great changes in the corrosion rate. If common salt reaches aluminum in contact with acid solution, the metal will corrode very rapidly because of its high solution rate in the hydrochloric acid formed. Arsenic in sulphuric acid decreases its action on iron by a large amount. Many other examples could be given, but these are sufficient to indicate the care that should be taken to test against the actual solution found in the plant. Changes in composition due to evaporation or absorption of moisture from the atmosphere, especially after draining a piece of apparatus, must be taken into account. An iron test piece immersed in concentrated sulphuric acid and exposed a few hours each day to saturated air showed almost three times the corrosion of another piece immersed in the acid continuously.

B. Specific Materials

In considering the fitness of a material of construction for use in chemical works, corrosion is usually the largest factor. Mechanical strength is also important, but a weak material may be given sufficient rigidity by reinforcing it with a stronger one, while in general no practical method can be used to give a material chemical resistance. The effect of small amounts of corroded material in the final product must also be considered. In the manufacture of some organic materials, picric acid, for example, danger from explosion results if metallic salts are present. With other products, a lowering of quality is produced; for example, iron saddens many dyes, while lead condenser coils give phenol an objectionable yellow color.

A problem in corrosion starts with the corrosive agent or the operation. The result desired is a proper material for the container. In the following sections the best materials for use under the specified conditions are grouped first under the heading of the corrosive agent and second under the general chemical engineering operation involved. This information is based on data included in the present report, a few extracts from the literature, and in some cases from what is accepted everywhere as sound practice. The order of men-

1. USE WITH CORROSIVE AGENTS

Corrosive Agent			Metals
Name	Concentration	Temperature	Resistant to Corrosion
		° C.	
Acetic anhydride		20–80	Iron, copper, lead, aluminum
Acid, acetic	Glacial	20–80	Iron, copper, aluminum, lead
Acid, benzoic	Vapor	250	Nickel, copper
Acid, chloracetic	Plant	20–100	Nickel, lead, copper
Acids, fatty (propionic butyric, etc.)	Trace water	100+	Aluminum
Acid, hydrochloric	10–30%	20–80	(Stoneware), special high silicon cast iron (special grades of Tantiron, Duriron, etc.), special hard lead
	1–5%	20–30	(Stoneware), lead (especially hard lead) monel metal.
Acid, mixed	$HNO_3.H_2SO_4$		Mild steel, high silicon cast iron
Acid, nitric	30–90%	20–30	Aluminum, high silicon cast iron (Tantiron, Duriron, Corrosiron, etc.)
	30–90%	50–80	High silicon cast iron
	10%	20–80	High silicon cast iron
Acid, sulphuric, fuming	100+%	20–100	Cast iron, high silicon cast iron, steel
	90–95%	20–100	Cast iron, high silicon cast iron, steel, hard lead
	10–25%	20–30	Lead, nickel, special high silicon cast iron
	10–25%	80–100	Special high silicon cast iron
	1–5%		Lead, brass, bronze, monel metal.
Acid, sulphurous	Strong	20–100	Lead, bronze
Benzaldehyde	Plant	20–30	Zinc, (drum containers)
Caustic, mixed	KOH/NaOH = 10/7, 25°–50° Bé.	100+	Cast iron (not too high in Si), steel
Caustic, soda	40–5 —° Bé.	20–100+	Cast iron (not too high in Si), steel

1. USE WITH CORROSIVE AGENTS.—*Continued*

Corrosive Agent			Metals
Name	Concentration	Temperature	Resistant to Corrosion
Dyes:			
Alizarine paste.....	+1–2% HCl	100+	Monel metal
Magenta solution..		20–100	Iron
Malachite green mother liquor ...		20–80	Lead, brass
Pontachrome brown, MW. paste.....		50–80	Cast iron
Pontachrome brown, 3a, paste.....		50–80	Cast iron (dye slightly dull)
Gases and vapors:			
Benzoic acid vapor.		250	Nickel, copper
Chlorine.....	Dry	20–80	Iron, steel
		100+	High silicon cast iron
Sulphur dioxide....	Dry	20–500	Cast iron
	Moist	20–200	Lead
	Moist	200–500	Cast iron
	Dry	boiling	Cast iron, steel
Mono-nitrochlor-benzol—moist....		boiling	Brass
Intermediates:			
Chlorbenzol.....			Iron, steel
Brown acid mother liquor.....		20–80	Lead
H-acid nitration mixture.....		100	Lead (rather high corrosion)
Koch's acid.....		20–80	Lead
Oxy acid, 1 : 5.....		20–30	Lead (rather high corrosion)
p-nitrophenol.....		20–100	Lead
Phenylglycine mother liquor, ferrous...		20–80	Iron
Salts:			
Sodium hydrosul-phite.....	20%	20–30	Lead
Sodium hypochlor-ite.....	20%	20–30	Cast iron, steel
Sodium sulphide...	5–25%	20–100	Lead

tion indicates in general the relative resistance to corrosion, the material least corroded usually appearing first. If a common metal can be used with very little increased corrosion, over an expensive special alloy, the latter evidently will not receive first choice; in fact, if the cost is too high, it may not be on the list at all. Non-metals, such as stoneware, are only mentioned where nothing else is possible or conditions make it highly desirable for their use.

2. USE IN CHEMICAL OPERATIONS

Operation	Metal
Caustic kettles and autoclaves	Cast iron
	Cast steel (high pressure)
	Silver lined for special use
Caustic fusions	Cast iron (low silicon and 2–5% manganese best)
Chlorination:	
Dry chlorine lines	Iron, steel
Moist chlorine lines	(Earthenware) (enamel or asphalt lined)
Chlorinators	Cast iron, lead, enamel, steel, nickel, copper.
Distillation:	
Acetic acid, glacial	Copper, aluminum, high silicon cast iron
Fatty acids (propionic, butyric, etc.)	Aluminum
Nitric acid	High silicon cast iron, silica
Organic acid materials	Nickel, copper, silver lined iron and steel
Phenol	Cast iron, silver lined
Filtrations:	
Strong acids	Filtros
Weak acids	Monel metal cloth, filtros
Alkalies	Monel metal cloth
Electrolytic cells:	
Diaphragms: Alkaline liquors	Asbestos, alumina
Acid and Neutral liquors	Filtros
Electrodes: Product desired and surface considerations rather than corrosion are determining factors.	
Dye containers	Nickel, copper, enameled metal, wood.
Nitrations:	
Nitrators: Mixed acid	Steel, high silicon cast iron, lead, enameled metal
Strong nitric acid, low temperature	Aluminum
Fume lines	Aluminum, stoneware
Denitrating recovery systems	Stoneware, high silicon cast iron
	Lead
Reductions	Cast iron, lead
Sulphonations	Cast iron, lead

3. *General Notes.*—The impurities in iron and steel and the addition of other metals have a considerable effect on the rate of corrosion. Copper in small amounts (1 per cent or less) increases the resistance to acids. Phosphorus and sulphur may increase the corrosion if present in sufficiently large amounts. Manganese in the usual quantity has little effect. High silicon (20 per cent +) cast irons are very resistant; this quality is very much increased by the addition of metals such as nickel and copper. Graphitic carbon probably protects cast iron somewhat by forming a protective coat as the corrosion progresses. Strong nitric and fuming sulphuric acid appear to penetrate cast iron without corroding the mass of the metal; the structure is very much weakened in such cases, making it unsafe for pressure vessels.[42]

[42] *J. Soc. Chem. Ind., 38,* 31T (1919).

For certain weak acids and in operations where metals introduce objectionable impurities, wood is very useful. Hard woods in general give the best service. Cypress and hard maple are excellent, but the latter is expensive. California red wood has come into considerable use. Chemical stoneware can be used with almost any acid. Alkalies attack both woods and stoneware. Brasses, bronzes, and special alloys such as monel metal are very useful against weak acids. Enameled steel is similar to stoneware in its properties, but rather fragile. Where considerable stress is encountered, as, for example, with stirrers, enameled steel may be preferable to cast iron. Steel alone should not be used with cast iron because of danger from electrolytic action.

Corrosion Prevention

A material non-resistant to corrosion may be protected by:

A. Application of a coating to the surface.
B. Additions during process of manufacture forming an integral part of the material.
C. Electrochemical means.

Among the different types of coating may be mentioned:

1. *Paints.*—A complete discussion of this subject is contained in Cushman and Gardner, "Corrosion and Preservation of Iron and Steel." Asphalt paints are especially useful in chemical works.

2. *Metallic Coatings.*—Metals may be applied to a surface either electrolytically or by dipping in a molten bath. Zinc and tin are the more common metals used for protection, especially against atmospheric corrosion. Galvanized and tinned metals are of little or no use in chemical plants for preventing corrosion. Tin is useful against alkalies and both tin and zinc coated metals are made use of where danger from contamination with other metals is present, particularly in protecting dyes and textile chemicals from contact with iron. Practically no tinned metal is perfectly coated, resulting in greatly accelerated corrosion at exposed spots. There is no reason why other metals, especially nickel, should not be used as protective coats against actual chemical corrosion in some instances. Silver lined autoclaves and stills are fairly common. Aluminum applied to iron by the calorizing process [43] protects against oxidation or high

[43] *Trans. Am. Electrochem. Soc., 27,* 253 (1915).

temperature corrosion by air. Silicon tetrachloride in contact with iron at high temperatures deposits metallic silicon upon the surface of the latter.[44] The high resistance of silicon to reagents at once suggests the use of such a process in giving a chemical resistant material.

3. *Enamels.*—Glass enameled chemical apparatus is in more or less common use at present. It is rather fragile, requiring some care to prevent chipping due to temperature changes and mechanical handling. Enamels of this type vary considerably in their resistance against different chemicals. Corrosion tests should always be made. Glass enamels are, of course, not used against alkalies. A certain class of enamels (Bakelite,[45] sodium silicate, etc.) may be applied as a liquid varnish and then baked at a moderately low temperature. They are fairly resistant, but brittle. An inert filler may frequently be used to advantage with this class of enamels.

4. *Protective Oxides.*—The protection afforded iron by a continuous coating of magnetic oxide has been made use of by Barff, Bower, Well, and others who produce an artificial coating of this type by passing steam or gases over the hot metal. A discontinuous coat will accelerate the corrosion of exposed metal.

5. *Protective Linings.*—By the attachment of thin plates of resistant material of low mechanical strength to a supporting framework of strong metal, a satisfactory container is sometimes obtained. Lead lined tanks and pipes are frequently used. Ebonite or hard rubber has been vulcanized on steel for use with hydrochloric acid.[46]

The disadvantage of all surface coating methods is the difficulty of obtaining a perfect coat covering the entire surface. Subsequently considerable care is required to keep this coating continuous. It is far better to use a single homogeneous material.

A large number of alloys are much more resistant to corrosion than single metals. Small additions during the process of manufacture may increase the resistance greatly. The lessened corrosion of steel containing copper has already been mentioned. The same metal or nickel added to high silicon cast iron increases the already high resistance of the latter. Nickel is especially useful as a component of alloys with low corrosion rates.

[44] *Chem. Trade J., 64,* 99 (1919).
[45] *Trans. Am. Electrochem. Soc., 15,* 593 (1909).
[46] Brit. Pat. 124997, British Dyes, Ltd.

A metal may also be protected by decreasing its effective potential against the corroding solution. This may be accomplished by contact with a more electro-positive material, or by making the metal to be protected the cathode by proper connections with a direct current generator and suspended anode. The latter has not been used in practice, and the former would be of little use in protecting chemical apparatus, although it has had some application in the prevention of boiler corrosion. Inhibitive paints, protecting because of the electrochemical character of the pigments, and useful in cases of atmospheric corrosion, would also be of little use for prevention of chemical corrosion. (See page 142 for discussion.)

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FIGURES—GRAPHICAL INTERPRETATIONS

FIG. 1. Effect of Concentration upon Corrosion of Aluminum by Nitric Acid.

FIG. 2. Effect of Concentration upon Corrosion of Aluminum by Mixed Acid.

FIG. 3. Effect of Concentration upon Corrosion of Aluminum by Acetic Acid.

FIG. 4. Effect of Concentration upon Corrosion of Mild Steel by Dilute Mixed Acid.

FIG. 5. Effect of Concentration upon Corrosion of Lead by Dilute Mixture of Sulphuric and Hydrochloric Acid.

FIG. 6. Effect of Time of Exposure upon Corrosion.

FIG. 7. Effect of Time of Exposure upon Corrosion (Long Time).

FIG. 8. Effect of Time of Exposure in Laboratory Test upon Rate of Corrosion Results.

FIG. 9. Effect of Temperature upon Rate of Corrosion of Aluminum in Nitric Acid (Sp. Gr. 1.42).

FIG. 10. Effect of Temperature upon Rates of Corrosion of Cast Iron, Lead, and Steel in Hydrochloric Acid (10 per cent).

FIG. 11. Effect of Temperature upon Log Rate of Corrosion of Aluminum in Nitric Acid (Sp. Gr. 1.42).

FIG. 12. Effect of Temperature upon Log Rate of Corrosion of Cast Iron, Lead, and Steel in Hydrochloric Acid (10 per cent).

TABULATION OF CORROSION DATA

Notes on Tabulations

Method Number.—

1. Standard Jackson Laboratory test.
2. Older tests, time of exposure, and volume of solution low. Results are probably high in most cases.
3. Very old data or conditions unknown.

Reports of Data.—

J—Jackson Laboratory Corrosion File.

C—Jackson Laboratory Card File for Corrosion Data.

E—Eastern Laboratory.

S—Experimental Station.

Temperature effect recorded in separate table (Table IV) if determinations were made at more than two temperatures.

Velocity effect recorded in separate table (Table VI).

Hardness (H) measured with Shore scleroscope.

TABLE I

EFFECT OF CONCENTRATION OF CORRODING SOLUTION UPON RATE OF CORROSION

Metal: Aluminum[46] Solution: Nitric Acid Temperature: 20° C.		Aluminum[46] Mixed Acid 20° C.			Aluminum[46] Nitric Acid 25–30° C.	
Conc. HNO_3 % by Wt.	Rate of Corrosion. Inches Penetration per Month	Conc. H_2SO_4 % by Vol.	HNO_3 % by Vol.	Rate of Corrosion. Inches Penetration per Month	Conc. HNO_3 % by Wt.	Rate of Corrosion. Inches Penetration per Month
99–100	0.000005	100	0	0.0054	40	0.0087
96.1	0.00002	90	10	0.0077	50	0.0080
90.8	0.00013	80	20	0.0078	60	0.0052
89.0	0.00044	70	30	0.0079	70	0.0031
69.6	0.00133	60	40	0.0079		
55.8	0.00177	50	50	0.0078		
40.7	0.00244	40	60	0.0075		
22.2	0.00310	30	70	0.0068		
9.3	0.00133	20	80	0.0051		
4.4	0.00088	10	90	0.0033		
		0	100	0.0007		

Metal: Aluminum[47] Solution: Acetic Acid Temperature: 20° C.		Aluminum[47] Acetic Acid Boiling	
Conc. % Acetic Acid	Rate of Corrosion. In. Penetration per Month	Conc. % Acetic Acid	Rate of Corrosion. In. Penetration per Month
99.2	0.00000	99.9	0.00031
90	0.00001	98	0.00155
60	0.00003	90	0.00732
10	0.00004	80	0.01307
1	0.00005	70	0.01461
0.5	0.00006	60	0.01805
0.25	0.00008	50	0.01849
0.1[48]	0.00010	40	0.02180
0.02[48]	0.00014	20	0.02360
0.004[48]	0.00004	10	0.02578
		5	0.02700
		1	0.05320
		0.2	0.03410

[46] Data calculated from Seligman and Williams, *J. Soc. Chem. Ind.*, *35*, 665 (1916).

[47] *J. Soc. Chem. Ind.*, *35*, 88 (1916); *36*, 409 (1917).

[48] 10–15° C. temperature.

Metal: Mild Steel Solution: Dilute Mixed Acid Temperature: 25° C. +			Lead Dilute Mixture of H_2SO_4 & HCl 25° C. +		
Conc. % H_2SO_4	% HNO_3	Rate of Corrosion. In. Penetration per Month	Conc. % H_2SO_4	% HCl	Rate of Corrosion. In. Penetration per Month
20	0	0.251	20	0	0.0001
18	2	2.802	18	2	0.0032
15	5	8.38	15	5	0.0179
10	10	11.32	10	10	0.0489
5	15	9.52	5	15	0.0856
2	18	8.56	2	18	0.1326

TABLE II

Effect of Time of Exposure upon Corrosion

Metal: Mild Steel Solution: Conc. Commercial H_2SO_4 (93%) Temperature: 22–27° C.		Mild Steel Sodium Hydrosulphite (20%) Conc. 22–27° C.		Mild Steel Com. H_2SO_4 (93%) 22–27° C.	
Time of Exposure t in hr.	Wt. of Metal Corroded per Unit Area $\frac{W}{A}$ in $\frac{\text{Gr.}}{\text{sq. in.}}$.	Time of Exposure t in hr.	Wt. of Metal Coroded per Unit Area $\frac{W}{A}$ in $\frac{\text{Gr.}}{\text{sq. in.}}$.	Time of Exposure t in hr.	Wt. of Metal Corroded per Unit Area $\frac{W}{A}$ in $\frac{\text{Gr.}}{\text{sq. in.}}$.
1.0	0.0054	1.0	0.0270		
3.0	0.0068	3.0	0.0358		
6.2	0.0112	6.25	0.0398		
26.7	0.0334	25.0	0.0495		
20.0	0.0216	26.75	0.0312	20.0	0.0157
49.5	0.0280	51.0	0.0309	49.5	0.0215
67.75	0.0255	70.25	0.0362	67.75	0.0254
91.5	0.0436	93.25	0.0398	92.5	0.0360
145.5	0.0459	147.0	0.0467	145.5	0.0516
216.0	0.0530	195.0	0.0537	216.0	0.0667
409.5	0.1241	411.0	0.1308	409.5	0.1080
727.0	0.2418	728.4	0.3826	716.5	0.1550
1,028.5	0.1799	1,030.0	0.6000	1,028.5	0.1996
				2,665.5	0.3330

Metal Aluminum, Solution 30% HNO_3, Temp. 27° C. ± 1°.

Time of Exposure t in Hrs.	Wt. of Metal Corroded per Unit Area. $\frac{W}{A}$ in $\frac{\text{Gr.}}{\text{sq. in.}}$
18.5	0.0135
24	0.0173
44	0.0287
88.5	0.0661
163.5	0.1332

TABLE III

EFFECT OF TIME OF EXPOSURE IN LABORATORY TEST UPON RATE OF CORROSION RESULTS

Metal: Mild Steel Solution: Conc. Com. H_2SO_4 (93%) Temperature: 22–27° C.		Mild Steel Sodium Hydrosulphite (20%) $Na_2S_2O_4$ 95% 22–27° C.		Mild Steel Conc. Com. H_2SO_4 (93%) 22–27° C.	
Time of Exposure hr.	Rate of Corrosion. Inches Penetration per Month.	Time of Exposure hr.	Rate of Corrosion. Inches Penetration per Month.	Time of Exposure hr.	Rate of Corrosion. Inches Penetration per Month
1.0	0.0308	1.0	0.1540		
3.0	0.0129	3.0	0.0681		
6.2	0.0103	6.25	0.0377		
26.7	0.0071	25.0	0.0113		
20.0	0.0062	26.75	0.0067	20.0	0.0047
49.5	0.0032	51.0	0.0035	49.5	0.0026
67.75	0.0021	70.25	0.0029	67.75	0.0021
91.5	0.0027	93.25	0.0024	92.5	0.0023
145.5	0.0018	147.4	0.0018	145.5	0.0021
216.0	0.0014	195.0	0.0016	216.0	0.0018
409.5	0.0017	411.0	0.0018	409.5	0.0016
727.0	0.0019	728.0	0.0030	716.5	0.0013
1,028.5	0.0010	1,030.0	0.0033[49]	1,028.5	0.0012
				2,665.5	0.0007

Metal Aluminum, Solution 30% HNO_3, Temp. 27° C. ± 1°.

Time of Exposure hr.	Rate of Corrosion Inches Penetration per Month
18.5	0.0120
24	0.0119
44	0.0107
88.5	0.0123
163.5	0.0134

[49] Total rate, pitting corrosion included, = 0.0046 in/mo.

TABLE IV

EFFECT OF TEMPERATURE UPON RATE OF CORROSION

Metal		Solution			Method No.	Rate of Corrosion Inches Penetration per Month
Name	Description	Name	Description or Concentration	Temp. ° C.		
Copper		P-Nitro phenol	Saturated solution	0	2	0.00003
"		" "	" "	40	"	0.00037
"		" "	" "	60	"	0.00040
"		" "	" "	100	"	0.00062
Iron	Cast, soft, hardness =8					
"	do.	Acid, hydrochloric	10%	25	"	0.4381
"	do.	" "	"	40	"	0.6886
"	do.	" "	"	50	"	0.8089
"	do.	" "	"	60	"	1.0140
"	do.	" "	"	70	"	1.2615
"	do.	" "	"	80	"	1.5202
"	do.	" "	"	90	"	1.7606
"	do.	" "	"	110	"	.....
Lead		Acid, hydrochloric	20%	25	3	0.007
"		" "	"	50	"	0.028
"		" "	"	75	"	0.038
"		" "	"	100	"	0.120
"		" "	10%	25	2	0.0022
"		" "	"	40	"	0.0039
"		" "	"	50	"	0.0073
"		" "	"	60	"	0.0108
"		" "	"	70	"	0.0215
"		" "	"	80	"	0.0286
"		" "	"	90	"	0.0414
"		" "	"	110	"	0.2050
"		" "	5%	25	3	0.001
"		" "	"	50	"	0.002
"		" "	"	75	"	0.004
"		" "	"	100	"	0.003
"		" "	1%	25	3	0.001
"		" "	"	50	"	0.002
"		" "	"	5	"	0.004
"		" "	"	100	"	0.003

Metal		Solution			Method No.	Rate of Corrosion Inches Penetration per Month
Name	Description	Name	Description or Concentration	Temp. ° C.		
Lead		Acid sulphuric	33.3% + sodium chloride 6.7%	10	3	0.0001
"		" "	" " " "	20	"	0.0007
"		" "	" " " "	40	"	0.0008
"		" "	" " " "	60	"	0.0007
"		" "	" " " "	80	"	0.0032
"		" "	" " " "	100	"	0.0148
"		" "	31.0% + " " 17%	5	3	0.0078
"		" "	" " " "	0	"	0.0081
"		" "	" " " "	50	"	0.0146
"		" "	" " " "	75	"	0.0339
"		" "	" " " "	100	"	0.0369
"		" "	8.3% " " 1.7%	20	3	0.0016
"		" "	" " " "	40	"	0.0019
"		" "	" " " "	60	"	0.0021
"		" "	" " " "	80	"	0.0022
"		" "	" " " "	100	"	0.0234
Lead		Caustic soda	25%	10	3	0.0004
"		" "	"	20	"	0.0004
"		" "	"	40	"	0.0002
"		" "	"	60	"	0.0005
"		" "	"	80	"	0.0007
"		" "	"	100	"	0.0014
Lead		p-Nitro phenol	Saturated solution	60	2	0.0012
"		" "	" "	40	"	0.0025
"		" "	" "	60	"	0.0038
"		" "	" "	100	"	0.0042
Steel	Mild, hardness = 23	Acid, hydrochloric	10%	40	2	0.0341
"	do.	" "	"	50	"	0.1005
"	do.	" "	"	60	"	0.2873
"	do.	" "	"	70	"	0.4060
"	do.	" "	"	80	"	0.9464

Metal	Solution	Temp., ° C.	Rate of Corrosion. Inches Penetration per Month	Log Rate of Corrosion. Log Inches Penetration per Month
Aluminum[60].....	Acid, Nitric,	0	0.00024	−3.62
	Commercial, Sp. Gr. 1.42	8	0.00058	−3.24
		20	0.0021	−2.68
		30	0.0049	−2.31
		40	0.0091	−2.04
		50	0.0201	−1.70
		60	0.0411	−1.39
		70	0.0784	−1.11
		80	0.1528	−0.82
		90	0.2786	−0.55
		100	0.4765	−0.32
		110	0.7000	−0.15
		120	0.9300	−0.03
Lead.....	Acid Hydrochloric 10%	25	0.0022	−2.66
		40	0.0039	−2.41
		50	0.0073	−2.14
		60	0.0108	−1.97
		70	0.0215	−1.67
		80	0.0286	−1.54
		90	0.0414	−1.38
		110	0.2050	−0.69
Steel, Mild.....	Acid, Hydrochloric 10%	40	0.0341	−1.47
		50	0.1005	−1.00
		60	0.2837	−2.55
		70	0.4060	−0.39
		80	0.9464	−0.02
Iron, Cast.....	Acid, Hydrochloric 10%	25	0.4381	−0.36
		40	0.6886	−0.16
		50	0.8089	−0.09
		60	1.0140	0.01
		70	1.2615	0.10
		80	1.5202	0.18
		90	1.7606	0.25

Calculations.—

Representing data by straight line function,

$$\log C = \log A + BT$$

in which,

C = rate of corrosion $\frac{(dw)}{(dt)}$

T = temperature in °C

$\log A$ = the intercept on $\log C$ axis when $T = 0$

B = slope of line

[60] Data calculated from Seligman and Williams, *J. Soc. Chem. Ind.*, *35*, 665 (1916)

Aluminum in Nitric Acid:

$$\log A = -3.22$$
$$\log C = -3.22 + BT$$

At $\log C = 0$, $T = 109.5 \therefore B = \frac{3.22}{109.5} = 0.0294$

$$\log C = 0.0294T - 3.22$$

Rate of change of C with temperature, $\frac{dC}{dT} = 0.0294C$

Lead in Hydrochloric Acid:

$$\log A = -3.25$$
$$\log C = -3.25 + BT$$

At $\log C = -1.00$, $T = 103.5 \therefore B = \frac{2.25}{103.5} = 0.0217$

$$\log C = 0.0217T - 3.25$$

Rate of change of C with temperature, $\frac{dC}{dT} = 0.0217C$

Mild Steel in Hydrochloric Acid:

$$\log A = -2.82$$
$$\log C = -2.82 + BT$$

At $\log C = 0$, $T = 79.0 \therefore B = \frac{2.82}{79.0} = 0.0357$

$$\log C = 0.0357T - 2.82$$

Rate of change of C with temperature, $\frac{dC}{dT} = 0.0357C$

Cast Iron in Hydrochloric Acid:

$$\log A = -0.51$$
$$\log C = -0.51 + BT$$

At $\log C = 0$, $T = 60 \therefore B = \frac{0.51}{60} = 0.0085$

$$\log C = 0.0085T - 0.51$$

Rate of change of C with temperature, $\frac{dC}{dT} = 0.0085$

TABLE V

EFFECT OF MISCELLANEOUS FACTORS IN LABORATORY TEST UPON RATE OF CORROSION RESULTS

Shape of Test Piece:

Metal: Lead. Pieces cast from same metal.
Solution: Hydrochloric Acid, 20 per cent, commercial.
Time of Exposure: 22.7 hrs.
Temperature of Solution: 25° C.

Ratio Length of Edges (inches) / Area (sq. in.)	Rate of Corrosion Inches Penetration per Month
3.17	0.0058
3.88	0.0052
5.56	0.0055
8.52	0.0062

Surface Finish of Test Piece:

Metal: Cast Iron.
Solution: Sulphuric Acid, 90 per cent.
Time of Exposure: 64 hrs.
Temperature of Solution: 25°–30° C.
Average Rate of Corrosion (inches penetration per month):
Test Pieces Roughened on Coarse Grinding Wheel..... 0.00205
Test Pieces Polished by Metallographic Grinding..... 0.00265

Metal: Copper.
Solution: Acetic Acid, 83 per cent.
Method of Test: Standard (48–96 hr. measurement).
Temperature of Solution: 27° C. + 1° C.
Average Rate of Corrosion (inches penetration per month):
Test pieces roughened on coarse grinding wheel and then covered with file scratches..... 0.00015
Test pieces polished by metallographic grinding..... 0.00014

Metal: Aluminum.
Solution: Nitric Acid, 30 per cent., C. P.
Method of Test: Standard (48–96 hr. measurement).
Temperature of Solution: 27° C. + 1° C.
Average Rate of Corrosion (inches penetration per month):
Test pieces roughened on coarse grinding wheel and then covered with file scratches..... 0.0117
Test pieces polished by metallographic grinding..... 0.0113

Volume of Corroding Solution:

Metal: Lead.
Solution: Acetic Acid, 80 per cent.
Time of Exposure: 65.8 hrs.
Temperature of Solution: 25° C. ± 1°.
Average Rate of Corrosion (inches penetration per month):
100 cc. solution per test piece..... 0.0035
200 cc. solution per test piece..... 0.0065
400 cc. solution per test piece..... 0.0066

Cleaning Test Pieces After Exposure:

Metal:	Mild Steel	Cast Iron	Lead	Lead
Method of Cleaning: (Cleaning methods indicated are several times as harsh as those ordinarily employed)	Scoured vigorously for ten minutes with "Old Dutch Cleanser" and piece of filter cloth.		Boiled ten minutes in distilled water, finally wiped vigorously with cheese cloth.	Boiled ten minutes in 20% ammonium acetate solution, finally washed in distilled water and wiped vigorously with cheese cloth.
Average Rate of Corrosion (in/mo.) (based on 96 hr. exposure, error is zero if two measurements are made)....	0.00003	0.00004	0.00001	0.00002

TABLE VI

Effect of Velocity on Corrosion of Lead

Solution			Velocity of Solution across Metal Surface ft./min.	Method No.	Rate of Corrosion. Inches Penetration per Month
Name	Description or Concentration	Temp. ° C.			
Acid	Hydrochloric 10%	25	0.0	2	0.0052
"	" "	"	0.2	"	0.0137
"	" "	"	0.6	"	0.0194
"	" "	"	0.8	"	0.0191
"	" "	"	3.0	"	0.0239
"	" "	"	6.6	"	0.0215
"	" "	"	9.0	"	0.0257
"	" "	"	13	"	0.0255
"	" "	"	25	"	0.0308
"	" 25%	"	16	2	0.0256
"	" "	"	28	"	0.0300
"	" "	"	29	"	0.0311
"	" "	"	33	"	0.0399
"	" 20%	"	0.2	1	0.0187
"	" "	"	0.3	"	0.0280
"	" "	"	0.5	"	0.0240
"	" "	"	0.7	"	0.0257
"	" "	"	1.0	"	0.0335
"	" "	"	1.1	"	0.0252
"	" "	"	2.6	"	0.0204
"	" "	"	2.8	"	0.0237
"	" "	"	3.6	"	0.0197
"	" "	"	3.8	"	0.0238
"	" "	"	5.6	"	0.0254
"	" "	"	5.9	"	0.0288
"	" "	"	9.2	"	0.0325
"	" "	"	9.7	"	0.0351
Acid	Sulphuric 20%	25	8.4	2	0.00031
"	" "	"	13	"	0.00032
"	" "	"	18	"	0.00028
"	" "	"	35	"	0.00028
"	" "	"	8.4	2	0.00055
"	" "	"	11	"	0.00048
"	" "	"	16	"	0.00048
"	" "	"	17	"	0.00049
"	" "	"	97	"	0.00017
"	" "	"	155	"	0.00016
"	" "	"	300	"	0.00086
"	" "	"	260	3	0.0017
"	" 9"	"	290	"	0.0010
"	" "	"	320	"	0.0020
"	" "	"	350	"	0.0034
"	" "	"	280	"	0.00020
"	" "	"	190	"	0.00016
Acid	Acetic Glacial	25	At rest		0.007
"	" "	25	Impact		0.0458

TABLE VII

MEASUREMENTS OF DIRECT E.M.F. BETWEEN METALS

Electrodes		Solution		Temp. ° C.	Electromotive Force, Millivolts
−	+	Name	Concentration		
Iron, cast	Copper	Caustic, mixed	25–50° Bé, KOH/NaOH = 10/7, some CO_2		1.5–10.0
	Steel, mild	Acid, sulphuric	99%+5% Oleum (65%)	25	3.5
				95	50
" "	" "	" "	99%	25	14.75
" "	" "	Naph. sulf. mass		40	50
" "	" "	" " "		25	1.5
" "	" "	" " "		25	50
" "	" C. R.	Acid, sulphuric	60%	50	19
" "	" Rivet	" "	"	50	21
" "	" Pipe No. 1	" "	"	50	50
Steel, rivet	Pipe (No. 1)	" "	"	50	27
" "	Boiler plate No. 1	" "	"	50	30
" "	" " No. 2	" "	"	50	1
" C. R.	Pipe No. 1	" "	"	50	15
" C. R.	Steel rivet	" "	"	50	10
" C. R.	" boiler plate (No. 2)	" "	"	50	10
" boiler plate (No. 1)	Pipe (No. 1)	" "	"	50	50
" " " (No. 1)	" (No. 2)	" "	"	50	36
" " " (No. 1)	" (No. 3)	" "	"	50	39
" " " (No. 1)	Steel rivet	" "	"	50	1
" boiler plate (No. 2)	Pipe (No. 2)	" "	"	50	20
" " " (No. 2)	" (No. 3)	" "	"	50	30
Pipe No. 1	Steel boiler plate (No. 2)	" "	"	50	33
Pipe (Hydr.)	" " " (No. 1)	" "	"	50	32.5
" "	" " " (No. 2)	" "	"	50	50
Brass (No. 2)	" " " (No. 1)	" "	"	50	7
" "	" " " (No. 2)	" "	"	50	6
" "	" " "	" "	"	50	5
Iron	Charcoal steel	Caustic, mixed	25–50° Bé, KOH/NaOH = 10/7, some CO_2	25	0.3
"	" "	" "	do.	115	1.0
Steel	" "	" "	do.	25	0.0
"	" "	" "	do.	115	0.5

TABLE VIII

Corrosion of Metals by Solutions at Rest

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
Alloy	Spec. Lumen Bearing Co.	Acid	1.55% calc. as H_2SO_4. Wood digestion in alcohol plant	80	3	0.00028
"	Ceco, Al + small % rare earths	" acetic	20%	25	1	0.0022
			20	B.P.		0.0190
			60	25		0.0019
			60	B.P.		0.0180
			100	25		0.00011
			100	B.P.		0.00039
			Acid Anhydride			
"	" " "	" " +acetic anhyd.	90% 10%	25	1	0.000493
			90 10	B.P.		0.235
			40 60	25		0.000214
			40 60	B.P.		0.220
			20 80	25		0.000087
			20 80	B.P.		0.0181
"	" " "	Acid, nitric	5%	25	1	0.0205
			5	50		0.0562
			50	25		0.0731
			50	50		1.130
			63 (comm.)	25		0.0655
			63 (C.P.)	25		0.0918
			63 (comm.)	50		0.230
			63 (C.P.)	50		0.288
			95	25		0.00072
			95	50		0.00340

TABLE VIII—*Continued*

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
Alloy	Ulcaloy (United Lead Co.)					
	No. 1 Pb–Cu	Acid, nitric	90%	25	3	0.15
			90	70–80		0.78
	No. 2 Pb–Cu	" "	50	25		15.16
	No. 1 Pb–Cu	" sulphuric	5	25		0.002
			5	70–80		0.006
	No. 2 Pb–Cu	" "	5	25		0.0000
			5	70–80		0.006
	No. 3 Pb–Cu	" "	5	25		0.000
			5	70–80		0.000
Aluminum		" acetic	20	25	1	0.000034
			20	B.P.		0.0185
			60	25		0.000033
			60	B.P.		0.0183
			100	25		0.000008
			100	B.P.		0.000019
	Pure sheet	" "	20	25		0.0030
			20	B.P.		0.0230
			60	25		0.0021
			60	B.P.		0.0170
			100	25		0.056
			100	B.P.		0.000014
"		Acetic anhydride	C.P.	25	1	0.00002
		" "	C.P.	60		0.00043

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
Aluminum		Acid, mixed	40% H_2SO_4, 60% HNO_3	20	3	0.0075
			30 70			0.0068
			20 80			0.0051
			10 90			0.0033
			0 100			0.0007
			100 0			0.0054
			90 10			0.0077
			80 20			0.0078
			70 30			0.0079
			60 40			0.0079
			50 50			0.0078
		" nitric	30% (roughened)	27	1	0.0117
			(polished)			0.0113
"	Unannealed sheet	" "	C.P. 70%		3	0.0031
			60			0.0052
			50			0.0080
			40			0.0087
"	" "	" "	69.6%	20		0.00133
			89.0			0.00044
			90.8			0.00013
			96.1			0.0002
			99.5			0.000005
"	" "	" sulphuric	5%	25	(25 hr.)	0.007
			10			0.013
			20			0.010

TABLE VIII—*Continued*

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
			30%			0.017
			40			0.020
			40			0.020
			50			0.039
Aterite	Cu 60.6, Ni 10.8, Zn 27.3, Sb 0.4, undetermined 0.9	" acetic	Glacial	31	3	0.0004
		" sulphuric	75%	B.P.	3	0.02
				100		0.0004
				70		0.0001
				31		0.0004
Bakelite	Dilecto	" acetic	99%	25	1	0.0031
		" hydrochloric	30	100	1	0.0903
		" nitric	68	25	1	0.0896
		Oil	Lubricating	130	1	0.034
Brass	Cast rough	Acid, mixed	98% H_2SO_4, 2% HNO_3	50	3	0.0089
"	" "	" 1.55% calc. as sulphuric—Wood digestion in alcohol plant		80	3	0.00028
"	Sheet	Alum solution	38° Bé	100	1	0.00721
Brick	Chemical ware	Sodium hydroxide	30%	90	1	0.195
		" sulphide		90		0.072
		Above mixed	NaOH 15%, Na_2S 15%	90		0.094
Bronze	BB	Acid, 1.55% calc. as sulphuric—Wood digestion in alcohol plant		80	3	0.00074
"	Cramp's	do.				0.00012
"	Lead	do.				0.00034

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
Bronze	Manganese	do.				0.00016
"	" Parson's	do.				0.00012
"	Phospher	do.				0.00021
"	Tin	do.				0.00023
"	Zinc-lead	do.				0.00026
"	Tobin	Alum solution	38° Bé	100	1	0.00726
Cement	Positive seal	Acid, acetic	80%		1	0.001213
			99+			0.00391
			80			0.00054
			99+			0.003067
Copper		Acetic anhydride		75	3	0.0040
				25		0.0002
"		Acid, acetic	32.96%	100	3	0.00172
			68.21	105		0.001623
			83.25	110		0.000032
			95.54	115		0.000254
			97.85	119		0.000223
			20	25	1	0.000128
			20	B.P.		0.00555
			60	25		0.00047
			60	B.P.		0.00101
			100	25		0.00069
			100	B.P.		0.0229
			83 (roughened)	27		0.00015
			83 (polished)	27		0.00014
			Glacial	25	3	0.0015
			"	50		0.0550
		" " plus acetic anhydride	20% acid, 80% anhyd.	25	1	0.000148

TABLE VIII—*Continued*

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
			20% 80%	B.P.		0.0269
			20 80	100		0.0095
			20 80 (air pres.)	100		0.0660
			40 60	50		0.00422
			40 60 (air pres.)	50		0.00355
			90 10	25		0.00050
			90 10	B.P.		0.0414
			40 60	25		0.000079
			40 60	B.P.		0.0393
Copper		Acid, chloracetic	Sp. Gr. 1.358 at 50° C.	100	1	0.0218
"		" hydrochloric	1.8%	25	1	0.00928
"			35.5	B.P.		0.0903
"		" nitric	3	25	1	0.00161
"	Very pure	" 1.55% calc. as sulphuric—Wood digestion in alcohol plant		80	1	0.0005
"		Caustic $\frac{KOH}{NaOH} = \frac{10}{7}$	25–50° Bé	B.P.	3	0.0016
"		Rongalite solution	90%	75	2	0.00047
						0.00035
Iron	Cast	Acid, acetic	20%	25	1	0.0591
				B.P.		0.213
			60	25		0.746
				B.P.		0.956
			100	25		0.0032
				B.P.		0.0192
			20 (0.7% As_2O_3)	25		0.0036
		" " plus acetic anhydride	20% acid, 80% anhyd.	25	1	0.00219
				B.P.		0.0121
			40 60	25		0.00161
				B.P.		0.0502
			90 10	25		0.0049

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
Iron				B.P.		0.113
"	" Soft H=8	Acid, chloracetic	Sp. Gr. 1.358 at 50° C.		1	0.0238
"	" " "	" hydrochloric	10%	20–30	3	0.256
				80–88		Very high
			27	20–30		0.36
				80–88		Very high
			10 (0.7% As_2O_3)	250		0.00026
"	" " "	" mixed	60% H_2SO_4, 23.5% HNO_3	25	1	0.00272
						0.00170
			60 23.5	25		0.00241
			(Contact with mild steel)			0.00153
"	" " "	" nitric	10%	20–30	3	0.315
				80–88		0.611
			85–90	20–30		0.0345
				80–88		0.49
"	" " "	" sulphuric	10	20–30	3	0.197
				80–88		0.248
			93	20–30		0.001
				80–88		0.019
			99	40		0.010
			Oleum	20–30		0.0013
				80–88		0.0139
			93	25 (30-day test)		0.0015
			10 (0.7% As_2O_3)	25	1	0.0786
			1.55 (roughened)	80	3	0.0423
			(polished)			0.0492
"	" " "	Antimony pentachloride	100	100	1	0.0081
"	" " "	" trichloride	100	100	1	0.00071

TABLE VIII—*Continued*

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
Iron	Cast, H =8	Caustic, mixed, $\frac{KOH}{NaOH} = \frac{10}{7}$	25–50° Bé	B.P.	3	0.0491
			40–50° Bé	B.P.	3	0.0025
			25–50° Bé	B.P.	2	0.0295
		p-Nitraniline $\frac{PNA}{NH_3(28\%)} = \frac{1}{4.66}$		160	3	Unaffected
		Nitrobenzene $\frac{NB}{(87\%)HNO_3} = \frac{8}{1}$		55	1	0.0508
		m-Nitrochlorbenzol, dehydrated			2	0.0009
		Sodium hydrosulphite	20%, Comm. (95%)	25	2 (30-day test)	0.0081
	Wrought Corrosiron No. 42	Caustic soda	50–40° Bé	B.P.	2	0.0025
		Acid, hydrochloric	10%	20–30	3	9.0015
				80–88		0.0167
			27	20–30		0.0248
				80–88		0.154
	" No. 42	Acid, nitric	10%	20–30	3	0.0004
				80–88		0.002
			85–90%	20–30		0.00006
				80–88		0.0004
	" No. 42	" sulphuric	10%	20–30		0.0234
				80–88		0.0230
			93%	20–30		0.0001
				80–88		0.0001

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
			Oleum	20–30		0.003
				80–88		0.085
	Wrought Corrosiron No. 148	" hydrochloric	10%	20–30	3	0.001
				80–88		0.018
			27	20–30		0.0075
				80–88		9.124
		" nitric	10%	20–30	3	0.0000
				80–88		0.0001
			85–90	20–30		0.0000
				80–88		0.0000
Iron	Corrosiron No. 148	Acid, sulphuric	10%	20–30	3	0.0007
				80–88		0.0072
			93	20–30		0.0000
				80–88		0.0002
		" "	Oleum	20–30		0.0156
				80–88		0.121
	" No. 152	" hydrochloric	10%	20–30	3	0.001
				80–88		0.014
			27	20–30	3	0.0059
				80–88		0.193
		" nitric	10%	20–30	3	0.0004
				80–88		0.0016
			85–90	20–30		0.0000
				80–88		0.0001
		" sulphuric	10	20–30	3	0.001
				80–88		0.007
			93	20–30		0.0000
				80–88		0.0004
			Oleum	20–30		0.0141
				80–88		0.0895

TABLE VIII—*Continued*

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
Iron	Duriron	Acid, acetic	20%	25	1	0.00646
				B.P.		0.00779
			60	25		0.00066
				B.P.		0.00121
			100	25		0.000105
				B.P.		0.000985
			99.49 (NaCl present)	98	3	0.00040
	Duriron	Acetic anhydride	C.P.	60	1	0.000095
	Duriron	Acid, acetic	99	25	1	0.00012
				60		0.00019
			99.5	25		0.00012
				60		0.00019
		" + anhydride	Anhy. Acid			
			10% 90%	25	1	0.000055
			10 90	B.P.		0.000107
			60 40	25		0.00040
			60 40	B.P.		0.00095
			80 20	25		0.00013
			80 20	B.P.		0.0051
		" hydrochloric	10%	24		0.00163
			10	43		0.00503
			36.21	24		0.00424
			36.21	85		0.19000
		" sulphuric	25	25	3	0.00001
			25	80		0.00023
			2	140° F.	(Loss in 72 hrs.)	0.01
			5	140° F.	(Loss in 72 hrs.)	0.01
	Tantiron	Acid, hydrochloric	2	25	1	0.00081
			20	25	1	0.00063

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
			2%	60		0.00265
			20	60		0.01150
		" nitric	10	25	1	0.01180
			70	25		0.00078
			10	60		0.01560
			70	60		0.00252
		" sulphuric	1	25	1	0.00061
			10			0.00668
			20			0.00012
			50			0.00081
			100			0.00074
			1	60		0.00181
			10			0.00802
			20			0.00152
			50			0.00234
			100			0.00076
Lead		Acid, acetic	4	Room	1	0.00177
			3			0.00175
			2			0.00183
			1			0.00162
			0.5			0.00162
			5			0.0024
			10			0.0015
			20			0.0023
			40			0.0018
			60			0.0023
			Glacial 98%	25	2	0.007
				50		0.020
			" 99.5+5% S_2Cl_2	25		0.0002
				50		0.001
				75		0.021
				70	3	0.0006

TABLE VIII—*Continued*

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
Lead		Glacial saturated with lead acetate		70	1	0.0024
		Acetic,	79.9%	25		0.0066
		Glacial saturated with sodium sulphate		25		0.0044
		Acid, Chloracetic,	sp. gr. 1.358 at 50° C.	10		0.0547
		Acid, Hydrochloric	1%	25	3	0.001
				100		0.003
			5	25		0.0015
				100		0.0045
			10	25		0.001
				100		0.013
			20	25		0.007
				100		0.120
			comm'l 20%	25	2	0.0055
			35.5	25		0.091
				100		0.172
			10	70	3	0.0138
			10% sat'd with $PbCl_2$	70		0.0105
			Nitric 2%	70	2	0.2034
			2% + sat'd sol'n lead nitrate	70		0.4299
Lead		Acid, nitric	10%	25	(6 test hrs.)	0.609
"		" " plus $Na_2SO_4.10\ H_2O$	4.0% HNO_3, 0% Na_2SO_4	55	1	0.121
			1.0			0.108
			5.0			0.111
			10.0			0.00365
			20.0			0.00049
			30.0			0.00029

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
Lead		Acid, sulphuric	2.4%	25	1	0.000165
"		" "	5			0.000024
"		" "	105%	40	3	0.41
				70		0.95
"		" " +HCl	20% H_2SO_4, 0% HCl	25	2	0.0001
			18 2			0.0032
			15 5			0.0179
			10 10			0.0489
			5 15			0.0856
			2 18			0.1326
		Mixed acid	18 2% HNO_3			0.2478
			15 5			Very great
			10 10			" "
			5 15			" "
			2 18			" "
"		Acid, sulphuric + NaCl	8.3 1.7 NaCl	20	3	0.0016
				100		0.0234
			16.7 3.3	20		0.0002
				100		0.0265
			31.0 17.0	30		0.0081
				100		0.0369
			33.3 6.7	20		0.0007
				100		0.0148
			50.0 10	20		0.0010
				100		0.0034
"		" H_2SO_4 39.8%, H_2O 27.6%, R-salt 17.8%, Michler's hydrol 14.8%		100	1	0.0026
"		Caustic soda	5%	20	3	0.0011
				100		0.0035

TABLE VIII—*Continued*

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
		Caustic soda	15%	20	2	0.0004
				40		0.0002
				60		0.0005
				80		0.0007
				100		0.0014
			25	20	3	0.0004
				100		0.0010
			35	20		0.0003
				100		0.0005
Lead		Lead acetate, p-nitrophenol	Saturated solution	70	2	0.0783
			"	40		0.0025
				100		0.0042
		Sodium hydrosulphite,	20% comm. (95%)	25	3	0.00007
		Sodium sulfide	5%	25		0.002
				100		0.001
			10	25		0.001
				100		0.001
			15	25		0.001
				100		0.001
			20	25		0.001
				100		0.001
			25	25		0.001
				100		0.001
		Alum solution	38° Bé	100	1	0.00174
		Antimony trichloride	100%	100	1	0.0049
Lead—hard (Sb)		Acid, hydrochloric	1	20	3	0.0001

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
Lead, hard				100		0.0001
			5%	20		0.0001
				100		0.0006
			10	20		0.0002
				100		0.0006
			35	20		0.0010
				100		0.0024
		Acid, sulphuric	1	20		0.00002
				100		0.00006
			10	20	3	0.00006
				100		0.00003
			50	20		0.00001
				100		0.0002
			95	20		0.0001
				100		0.0041
" -tin solder		Rongalite sol'n	40	95–100	2	0.0005
			90			0.000185
		Polysulfide sol'n	Na_2S 8.3%, S 6.0%	B.P.	1	1.15
Meco metal	50% Pb, 50% Cu	Acid, HCl	20%	25	1	0.00140
			20	60		0.03040
			2	25		0.00020
			2	60		0.00153
		" H_2SO_4	1	45	1	0.00038
			10			0.00028
			20			0.00023
			50			0.00016
			100			0.00291
			1	30		0.00015
			10			0.00016

TABLE VIII—*Continued*

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
			20%			0.00013
			50			0.00004
			100			0.00186
Monel metal		Acid, acetic	99	25		0.00016
				60		0.0024
				100		0.040
		" H-	Disodium salt 20% sol'n	25		0.00007
				60		0.00012
				100		0.00015
		" HCl	10%	60		0.0071
				80		0.024
			20	25		0.0008
				60		0.054
				80		0.228
		" mixed	H_2SO_4 52.80, HNO_3 45.65			
			$HNOSO_4$ 1.28, H_2O 0.27	35		0.00070
						0.00072
Monel metal		Acid, nitric	30	25	1	Diss. readily
			76			" "
		" H_2SO_4	10	80		0.00054
				100		0.00059
			50	25		0.00021
				60		0.00135
			1	25		0.00009
				60		0.00076
				100		0.0035
			10	25		0.00025
				60		0.00043
		1.55% calc. as H_2SO_4. Wood digestion in alcohol plant		80	3	0.00020

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
		Alum sol'n	38° Bé	100	1	0.00517
		Caustic soda	20%	100	1	0.000004
		Sodium chloride	10	100		0.00043
		" hydrosulphite	$Na_2S_2O_4$ 10, NaOH 1	80		0.00017
Nickel		Acid, chloracetic	Sp. Gr. 1.358 at 50°	100	1	0.0019
		" hydrochloric	15%	25	1	0.0023
				200		Diss. readily
Pyralin		Acid, acetic	10	25	1	0.006
			99			Diss. readily
		" hydrochloric	10			0.0035
			37			0.063
		" mixed sulphuric and nitric	H_2SO_4 HNO_3			
			15% 5%	25	1	0.0043
			10 10			0.055
			5 15			0.0028
			65 32			Diss. slowly
			42 54			" "
			20 73			" "
		" nitric	10%	25	1	0.0024
			40			0.0035
		" sulphuric	10	25	1	0.148
			50			0.0046
			77			0.097
			93			Diss. readily
		Caustic soda	10	25	1	0.033
			25			0.292
			40			0.141
Silver	Coin	Acid hydrochloric	15	25	1	0.00104
			15	150	1	destroyed

TABLE VIII—*Continued*

Metal		Solution		Rate of Corrosion		
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
Steel	Mild	Acid, mixed	H_2SO_4 60%, HNO_3 23.5%	25	1	0.00104
		" "	" 72.5 " 27	25		0.00140
			" 52.8 " 45.65			
			$HNOSO_4$ 1.28 H_2O 0.27	35	1	0.000255
		Antimony pentachloride	100%	100	1	0.0118
		" trichloride	100	100	1	0.00030
		Sodium bisulphite	20	25	1	0.00135
"	Medium (tank)	Acid, hydrochloric	10	20–30	3	0.044
"	" "	" "		80–88		Very high
"	" (bar)	" "	10	20–30		0.435
"	" "	" "		80–88		Very high
"	" (tank)	" "	27	20–30		0.41
"	" "	" "		80–88		Very high
"	" (bar)	" "	27	20–30		0.26
"	" "	" "		80–88		Very high
"	" (tank)	" nitric	10	20–30	3	0.614
"	" "	" "		80–88		1.175
"	" (bar)	" "	10	20–30		0.414
"	" "	" "		80–88		0.741
"	" (tank)	" "	85–90	20–30		0.128
"	" "	" "		80–88		0.57
"	" (bar)	" "	85–90	20–30		0.009
"	" "	" "		80–88		0.29
"	" (tank)	" sulphuric	10	20–30	3	0.49
"	" "	" "		80–88		0.45
"	" (bar)	" "	10	20–30		0.25
"	" "	" "		80–88		0.325

Metal		Solution			Laboratory Work	Rate of Corrosion
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
Steel	Medium (tank)	Acid sulphuric	93%	20–30		0.0017
"	" "	" "		80–88		0.0194
"	" (bar)	" "	93	20–30		0.0019
"	" "	" "		80–88		0.0123
"	" "	" "	Oleum	20–30	3	0.0019
"	" "	" "	"	80–88		0.0016
"	" (tank)	" "	"	20–30		0.0015
"	" "	" "	"	80–88		0.0015
"	Mild	" , mixed aliphatic, 1.55% calc. as H_2SO_4		80	3	0.0067
"	" H =23	" acetic	97%	25	3	0.0049
"	"	" "	97	75		0.145
"	"	" "	97.5	25		0.0044
"	"	" "	98.0	25		0.0051
"	"	" "	98.0	75		0.177
"	"	" "	98.5	25		0.0057
"	"	" "	99.0	25		0.0056
"	"	" "	99.0	40		0.025
"	"	Sodium hydrosulphite	20% comm. (95% $Na_2S_2O_4$)	25	2	0.0044
"	"	Sodium hypochlorite		25	2	0.00003
"	"	Water, river, Delaware			2	0.0100

TABLE VIII—*Continued*

Metal		Solution			Laboratory Work	Rate of Corrosion
Name	Description	Name	Description or Concentration	Temp. ° C.	Method No.	Inches Penetration per Month
Tin	Block	Acid, acetic	20%	25	1	0.000412
				B.P.		0.000896
			60	25		0.000511
				B.P.		0.00131
			100	25		0.00160
						0.0140
		" " +anhydride	Acid Anhy.			
			10% 90%	25		0.00169
				B.P.		0.0103
			60 40	25		0.00140
				B.P.		0.0456
			80 20	25		0.00405
				B.P.		0.0588
Zinc	Galvanized iron	Polysulfide sol.	Na_2S 8.3%, S 6.0%	B.P.	1	0.0012
		Rongalite sol'n	40%	95–100	2	0.0077
			40			0.0032
			90	75		0.00784
			90			0.00775

SUMMARY

Solution		Temp. ° C.	Alloys, Special	Brass	Bronze	Copper	Iron, Cast	Iron, Special (corrosion)
Name	Concentration							
Acetic anhydride	—	25	—	—	—	0.0002	—	—
	—	75	—	—	Best	0.0040	—	—
Acid, mixed aliphatic	1.55% calc. as H_2SO_4	80	—	0.0003	0.00012	0.0012	—	—
Acid, acetic	Glacial	25	—	—	—	0.00020	—	—
	Glacial	31	0.0004	—	—	—	—	—
	Glacial	50	—	—	—	0.0550	—	—
Acid, benzoic vapor		250	—	0.0146	—	0.0075	0.0550	—
Acid, chloracetic	Sp. Gr. 1.36 at 50° C.	100	—	—	—	0.0218	0.0238	—
Acid, hydrochloric	35%	20	—	—	—	—	—	—
	—	100	—	—	—	—	—	—
	27%	20–30	—	—	—	—	0.36	0.0075
	—	80–88	—	—	—	—	Infin.	0.124
	20	20–25	—	—	—	—	—	—
	—	100	—	—	—	—	—	—
	10	20–30	—	—	—	—	0.256	0.001
	10	70	—	—	—	—	—	—
	Saturated with $PbCl_2$ 10%	70	—	—	—	—	—	—
	—	80–100	—	—	—	—	Infin.	0.014
	5							

SUMMARY

Solution		Temp. ° C.	Lead	Lead, Special Hard	Monel Metal	Nickel	Steel, Medium	Steel, Mild	Zinc
Name	Concentration								
Acetic anhydride	—	25	0.002	—	—	—	—	—	—
	—	75	0.006	—	—	—	—	—	—
Acid, mixed aliphatic	1.55% calc. as H_2SO_4	80	0.0044	—	0.0002	—	—	0.0067	—
Acid, acetic	Glacial	25	—	—	—	—	—	0.0056	—
	Glacial	31	—	—	—	—	—	—	—
	Glacial	50	—	—	—	—	—	—	—
	Glacial, 98.0%	25	0.007	—	—	—	—	0.0051	—
	Glacial, 98.0	50	0.020	—	—	—	—	0.1	—
	99.5% +5% S_2Cl_2	25	0.0002	—	—	—	—	0.028	—
	Glacial, 99.5 +5% S_2Cl_2	50	0.001	—	—	—	—	0.080	—
Acid, acetic		70	0.0006	—	—	—	—	—	—
Acid, acetic	Saturated with lead acetate	70	0.0024	—	—	—	—	—	—
Acid, acetic	79.9%	25	0.0066	—	—	—	—	—	—
Acid, acetic	79.9%, saturated with Na_2SO_4	25	0.0044	—	—	—	—	—	—
Acid, benzoic vapor	—	250	—	—	0.0032	0.0022	—	0.0596	0.0445
Acid, chloracetic	Sp. Gr. 1.36 at 50° C. Plant	100	0.0547	—	—	0.0019	—	0.0315	—
Acid, hydrochloric	35%	20	0.091	0.0010	—	—	—	—	—
		100	0.172	0.0024	—	—	—	—	—
	27	20–30	—	—	—	—	0.4	—	—
	—	80–88	—	—	—	—	Infin.	—	—
	20	20–25	0.006	—	—	—	—	—	—
	—	100	0.120	—	—	—	—	—	—
	10	20–30	0.001	0.0002	—	—	0.4	—	—
	10	70	0.0138	—	—	—	Infin.	—	—
	Saturated with $PbCl_2$ 10%	70	0.0105	—	—	—	—	—	—
	—	80–100	0.013	0.0006	—	—	—	—	—
	5%	20–25	0.0015	0.0001	—	—	—	—	—
	—	100	0.0045	0.0006	—	—	—	—	—
	2	100	—	—	0.0019	—	—	—	—
	1% +alizarin	100	—	—	0.0085	—	—	—	—
	1%	20–25	0.001	0.0001	—	—	—	—	—
	1% —	100	0.003	0.0001	—	—	—	—	—
Acid, mixed	Sulphuric 20%, hydrochloric 0%	25	0.0001						

Solution		Temp. ° C.	Alloys Special	Aluminum	Iron, Cast	Iron, Special (corrosiron)
Name	Concentration					
Acid, nitric	90%	25	0.13	—	0.0345	0.0000
	70%	25	0.14	0.0031	—	—
		80–88	—	—	0.49	0.0001
	30%	25	0.08	—	—	—
	10%	20–30	—	—	0.315	0.0000
	—	80–88	—	—	0.611	0.0001
Acid, sulphuric	Oleum	20–30	—	—	0.0013	0.003
		80–88	—	—	0.0139	0.085
	99%	40	—	—	0.010	—
	—	25	0.005	—	—	—
	93%	20–30	—	—	0.0015	0.0000

SUMMARY

Solution			Temp. ° C.	Lead	Steel, Medium	Steel, Mild
Name	Concentration					
Acid, mixed	Sulphuric 18%, hydrochloric 2%		25	0.0032	—	—
	15	5	25	0.0179	—	—
	10	10	25	0.0489	—	—
	5	15	25	0.0856	—	—
	2	18	25	0.1326	—	—
	Sulphuric 20%, nitric	0	25	0.2478	—	2.8
	2 to 18	2 to 18	25	Very great corrosion	—	8.0–11.0
Acid, nitric	90%		25	—	0.1	—
	70%		25	—	—	—
	—		80–88	—	0.5	—
	30%		25	—	—	—
	10%		20–30	—	0.5	—
	—		80–88	—	1.0	—
	2%		70	0.2034	—	—
	2% sat. with lead nitrate		70	0.4299		
Acid, mixed	Sulphuric 8.3%, sodium chloride	1.7%	20	0.0016	—	—
			100	0.0234	—	—
	16.7	3.3	20	0.0002	—	—
	—		100	0.0265	—	—
	31.0	17.0	20	0.0081	—	—
			100	0.0369	—	—
	33.3	6.7	20	0.0007	—	—
	—		100	0.0148	—	—
			20	0.0010	—	—
	50.0	10.0	100	0.0034	—	—
Acid, sulphuric	Oleum		20–30	—	0.0017	—
			80–88		0.001–0.2	—
	105%		40	0.41	—	—
	—		70	0.95	—	—
	99%		40	—	—	0.0089
	95%		20	0.0001	—	—
	—		25	—	—	—
	—		100	0.0041	—	—
	93%		20–30	—	0.0018	—

Solution		Temp. ° C.	Alloy Special	Brass	Copper	Iron, Cast	Iron, Special (corrosion)	Iron, Wrought
Name	Concentration							
Acid, sulphuric	75%	31	0.0001	—	—	—	—	—
	—	100	0.0004	—	—	—	—	—
	50%	20	—	—	—	—	—	—
	—	100	—	—	—	—	—	—
	25%	100	0.003	—	—	—	—	—
	10%	20–30	—	—	—	0.197	0.0007	—
	—	80–88	—	—	—	0.248	0.0072	—
Caustic soda	—	100	—	—	—	—	—	0.0025
Caustic soda and potash, mixed $\frac{KOH}{NaOH} = \frac{10}{7}$, 25°–50° Bé		Boiling	—	—	0.0016	0.0491	—	—
Organic materials: Koch's acid, presence of large excess Fe		55	—	—	—	0.05–0.16	—	—
Green, Malachite, mother liquor		80	—	0.0002	—	—	—	—
Green, Victoria, mother liquor		80	—	0.0004	—	—	—	—
Magenta solution plant		30–90	—	—	—	—	—	0.001–0.01
Mono-nitro-chlorbenzol, plant		—	—	0.0021	—	—	—	—
Mono-nitro-chlorbenzol, vapor		—	—	—	0.0061	—	—	—
Mono-nitro-chlorbenzol, dehydrated		—	—	—	—	0.0009	—	0.0008
Para-nitrophenol, saturated		40	—	—	0.0004	—	—	—
		100	—	—	0.0006	—	—	—

SUMMARY

Solution		Temp. °C.	Lead	Lead, Special Hard	Monel Metal	Nickel	Steel, Med.	Steel, Mild
Name	Concentration							
Acid, sulphuric	50%	20	0.00001	—	—	0.00011	—	—
		100	0.0002	—	—	—	—	—
	10%	20–30	—	0.00006	Resists	—	0.4	—
		80–88	—	0.00003	well	—	0.4	—
	1	20	—	0.00002	—	—	—	—
		100	—	0.00006	—	—	—	—
Caustic soda	5%	20	0.0011	—	—	—	—	—
		100	0.0035	—	—	—	—	—
	25%	20	0.0004	—	—	—	—	—
		100	0.0010	—	—	—	—	—
	35%	20	0.0003	—	—	—	—	—
	—	100	0.0005	—	—	—	—	—
Lead acetate		—	0.0783	—	—	—	—	—
Organic materials: 1.5 oxy acid process		—	0.079	—	—	—	—	—
Brown acid		35–50	—	—	0.03	—	—	—
H-acid nitration mixture		30–35	0.0175	—	—	—	—	—
H-acid nitration mixture + 30% H_2O		30–35	0.0021	—	—	—	—	—
Koch's acid, presence of large excess Fe		55	0.00005	—	—	—	—	—
Presence small am't. Fe		55	0.00005	—	—	—	—	—
No Fe present		25–50	0.0004	—	0.04	—	—	0.01–0.03
Green, Malachite, mother liquor		80	0.00005	—	—	—	—	Very slight
Green, Victoria, mother liquor		80	0.0006	—	—	—	—	—
Mono-nitro-chlorbenzol, vapor		—	Disintegrated	—	—	—	—	—
Mono-nitro-chlorbenzol, dehydrated		—	—	—	—	—	0.0006	—
Para-nitrophenol, saturated sol.		40	0.0025	—	—	—	—	—
		100	0.0042	—	—	—	—	—

Solution		Temp. ° C.	Copper	Iron, Cast	Iron, Wrought
Name	Concentration and Description				
Pontachrome brown	—	75	—	0.007	—
Sodium hydrosulphite	20% solution	25	—	0.0081	—
Sodium hypochlorite	—	25	0.0003	—	—
Water, river, Delaware					0.001

SUMMARY

Solution		Temp. °C.	Lead	Nickel	Steel, Mild	Zinc
Name	Concentration and Description					
Benzaldehyde	—	40	—	—	—	0.006
Phenylglycine	Ferrous mother liquor	25–75	—	0.0001	—	—
Pontachrome brown	—	75	—	—	—	—
Sodium hydrosulphite	20% solution	25	0.00007	—	0.0030	—
Sodium hypochlorite		25	0.1280	—	0.00003	—
Sodium sulphide	5%	25	0.002	—	—	—
		—	0.001	—	—	—
	10, 15, 20 and 25%	25	0.001	—	—	—
	10, 15, 20 and 25%	100	0.001	—	—	—
Water, river, Delaware		—	—	—	0.001	0.001

TABLE IX

Corrosion of Metals by Vapors

Metal		Vapor		Laboratory Test		Rate of Corrosion
Name	Description	Name	Desc. or Conc.	Temp. ° C.	Method No.	Inches Penetration per Month
Brass	Yellow (1)	Benzoic acid		250	1	0.0146
Brass	Yellow	Mono-nitrochlor-benzol			2	0.0003
Copper	Hardness +21(3)	Benzoic acid	Plant product	250	1	0.0075
Copper		Mono-nitrochlor-benzol			2	0.0061
Iron	Cast, hardness =8	Benzoic acid	" "	250	1	0.0550
Lead		Mono-nitrochlor-benzol			2	Completely disintegrated
Monel	Hardness =20	Benzoic acid	" "	250	1	0.0032
Nickel	Hardness =30	Benzoic acid	" "	250	1	0.0022
Sodium silicate coating on mild steel (8)		Benzoic acid	" "	250	1	0.00622
Sodium silicate coating on cast iron (9)		" "	" "	250	1	0.00472
Steel, mild, hardness =23		" "	" "	250	1	0.0596

Remarks:

1. Differential removal of zinc by vapor.
3. Hardness =11 after test.
8. Corrosion of metal reported.
9. Corrosion of metal reported.

TABLE X

Corrosion of Enamels and Coatings by Solutions and Vapors

Enamel or Coating	Solution or Vapor	Time of Exposure	Temp. ° C.	Results
Bakelite protective enamel No. 6 on steel cup	Acid, (wood digestion in alcohol plant), 1.55% calc. as H_2SO_4	8 days (8 hrs. each day)	80	Blistered and broke, exposing metal
Bakelite (baked) on steel	Acid, acetic 83.4%	5 days	25–30	Blistered and broke upon drying after test. Otherwise protected.
Enamel, Elyria blue	Acid, 5% HNO_2+HNO_3 +$Hg(NO_3)_2$	28 days	25	No visible action
Enamel, Limberg Foundry Co.	Acid, 5% HNO_2+HNO_3 +$Hg(NO_3)_2$	" "	25	Very slight action
Enamel, Stuart & Peterson	Acid, 5% HNO_2+HNO_3 +$Hg(NO_3)_2$	" "	25	Almost completely destroyed
Iron, galvanized	Benzaldehyde, 1.58% impurity	24 hrs.	40	0.0404" penetration per month
" "	" 9.55% "	" "	40	0.0017 " " "
Sodium silicate on cast iron	Benzoic acid vapor	12 hrs.	250	0.00622 " " "
Sodium silicate on mild steel	" " "	" "	250	0.00472 " " "
Thermometer scales:				
Acid, proof, SP 35,	HCl acid fume	1.25 hrs.	25	Attacked slightly
A. Weiskopf, Chicago	" " "			
Acid proof, SP, 50,	" " "			
A. Weiskopf, Chicago	" " "	1.25 hrs.	25	Almost completely destroyed

TABLE XI

DETERIORATION OF WOODS

Wood	Density (before testing) lb./cu. ft.	Increase in Weight	Increase in Volume	Increase in Density
		%	%	%
Very Hard				
Ebony*	71	7	7	0
Lignum Vitae	83	−2	11	−12
Hard				
Ash†	45	85	12	67
Beech†	49	66	11	49
Birch, White†	41	79	8	63
Maple, Rock†	43	70	8	58
Oak, White	44	54	0.7	52
Average	45	71	8	58
Soft				
Cypress†	38	76	−1	79
Fir†	45	85	18	58
Pine, Long Leaf, Yellow	29	140	5	130
Pine, white	26	150	0.2	158
Spruce	32	99	8	88
Average	34	110	6	103

Treatment during Test: 24 hrs. boiling in HCl acid (1%).

Notes: Appearance after drying—

* Cracked and warped.

† Warped but no cracks.

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Title Abbreviations

The title abbreviations are those used by *Chemical Abstracts* as given in the Annual Index, 1918. In addition, the following not mentioned in that journal are listed:

Brit. Pat	British Patent.
Dom. Eng	Domestic Engineering.
Fr. Pat	French Patent.
Ger. Pat	German Patent.
Inst. C. E	Institution of Civil Engineers.
J. Boston Soc. C. E	*Journal of the Boston Society of Civil Engineers.*
J. I. S. I	*Journal of the Iron and Steel Institute.*
J. Pharm. Chim. Schweig	
Mech. Eng	Mechanical Engineer.

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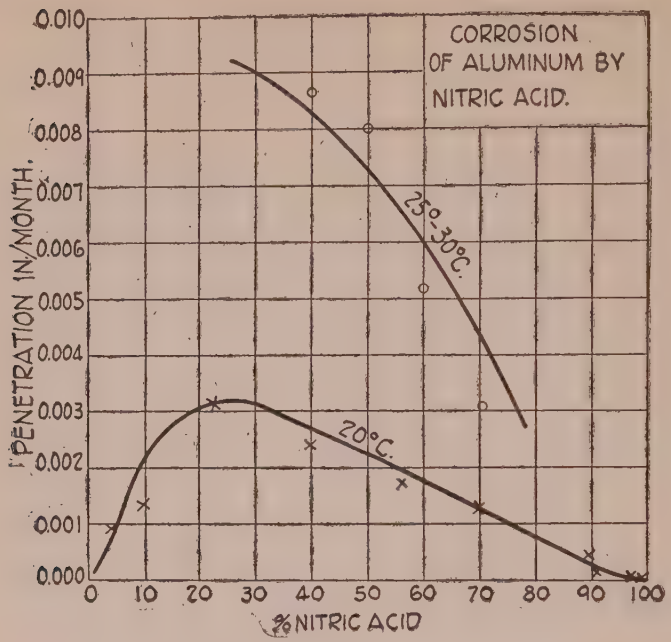
CORROSION
OF ALUMINUM BY
NITRIC ACID.
25°-30°C.
20°C.
PENETRATION IN/MONTH.
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0 10 20 30 40 50 60 70 80 90 100
% NITRIC ACID

FIG. 1

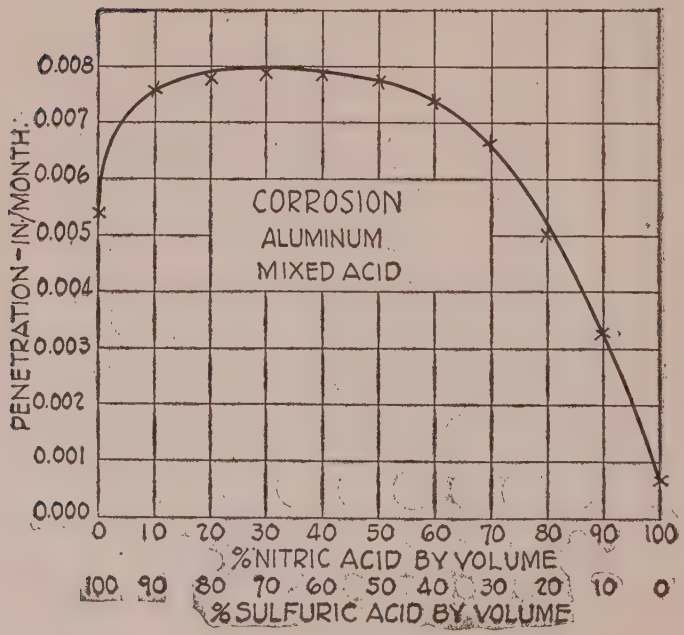
CORROSION
ALUMINUM
MIXED ACID
PENETRATION - IN/MONTH.
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0 10 20 30 40 50 60 70 80 90 100
% NITRIC ACID BY VOLUME
100 90 80 70 60 50 40 30 20 10 0
% SULFURIC ACID BY VOLUME

FIG. 2

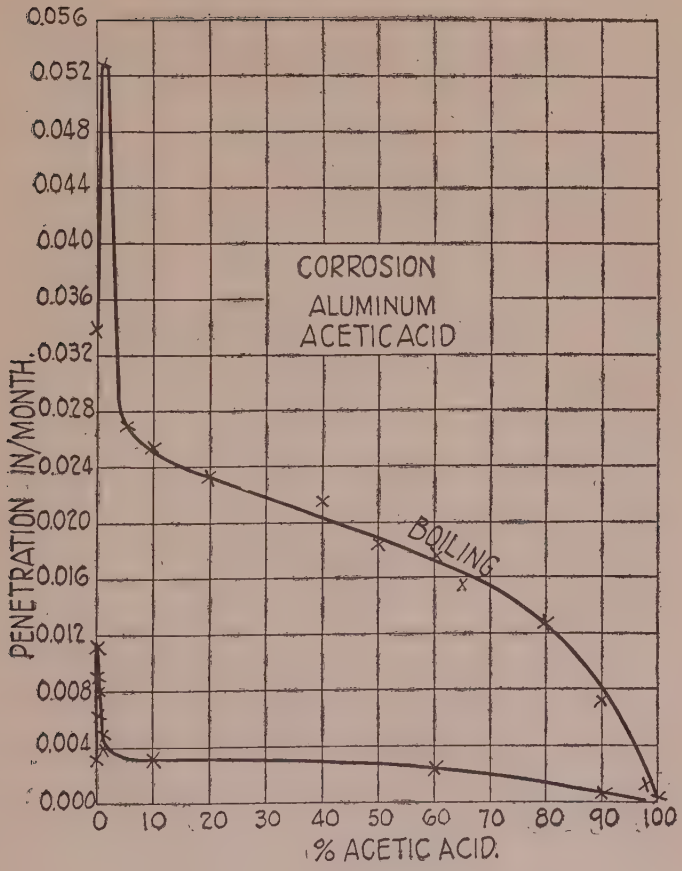
0.056
0.052
0.048
0.044
0.040
0.036
0.032
0.028
0.024
0.020
0.016
0.012
0.008
0.004
0.000
PENETRATION IN/MONTH.
CORROSION
ALUMINUM
ACETIC ACID
BOILING
0 10 20 30 40 50 60 70 80 90 100
% ACETIC ACID.

FIG. 3

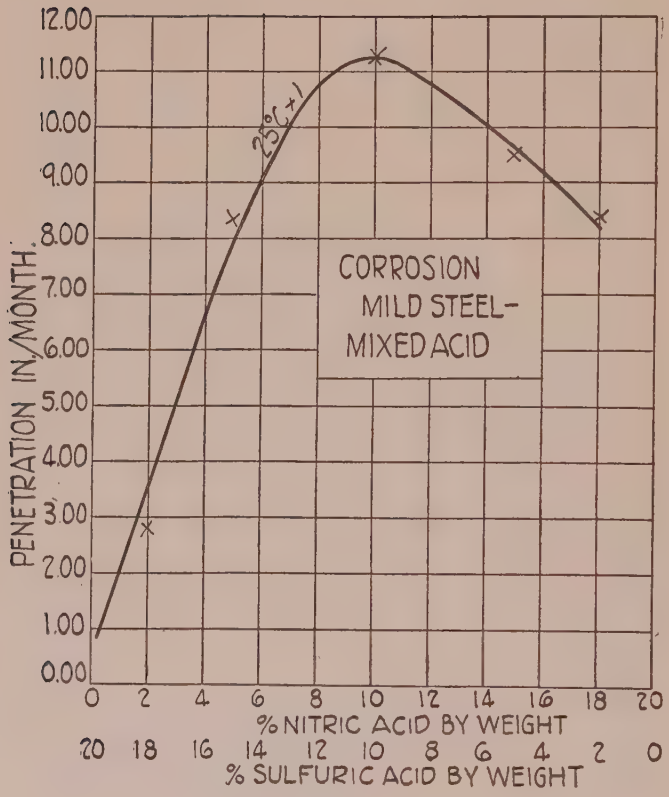
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
PENETRATION IN/MONTH.
25°C ± 1
CORROSION
MILD STEEL-
MIXED ACID
0 2 4 6 8 10 12 14 16 18 20
% NITRIC ACID BY WEIGHT
20 18 16 14 12 10 8 6 4 2 0
% SULFURIC ACID BY WEIGHT

FIG. 4

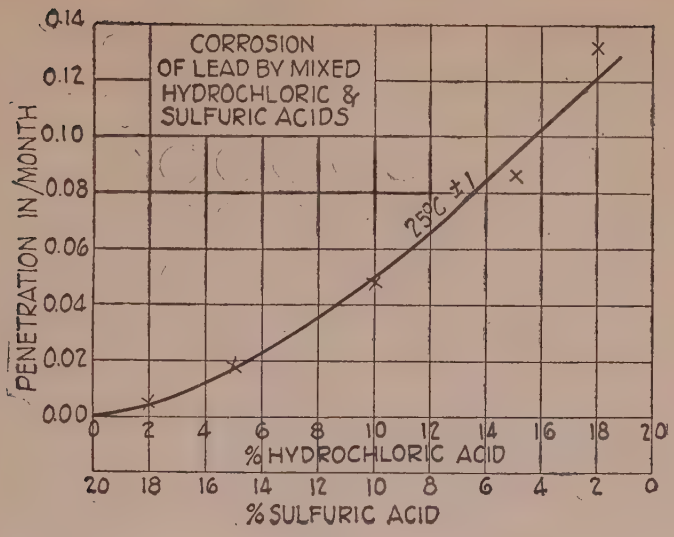
CORROSION
OF LEAD BY MIXED
HYDROCHLORIC &
SULFURIC ACIDS
25°C ± 1
PENETRATION IN/MONTH
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0 2 4 6 8 10 12 14 16 18 20
% HYDROCHLORIC ACID
20 18 16 14 12 10 8 6 4 2 0
% SULFURIC ACID

FIG. 5

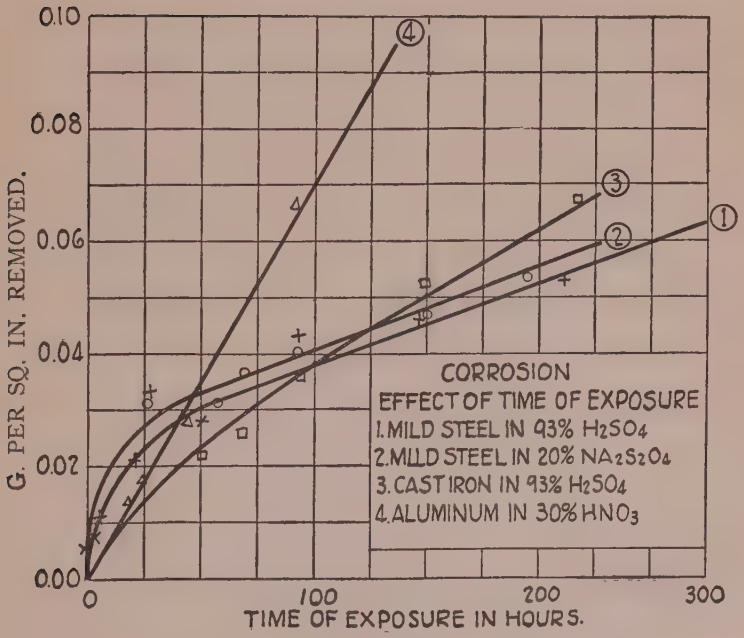
G. PER SQ. IN. REMOVED.
0.10
0.08
0.06
0.04
0.02
0.00
0 100 200 300
TIME OF EXPOSURE IN HOURS.
CORROSION
EFFECT OF TIME OF EXPOSURE
1. MILD STEEL IN 93% H_2SO_4
2. MILD STEEL IN 20% $NA_2S_2O_4$
3. CAST IRON IN 93% H_2SO_4
4. ALUMINUM IN 30% HNO_3
1
2
3
4

FIG. 6

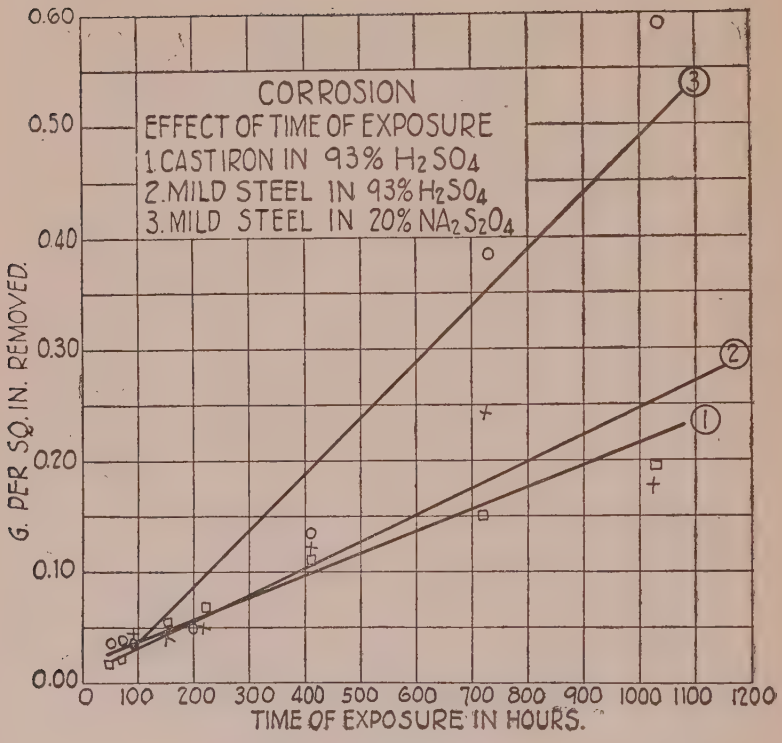
CORROSION
EFFECT OF TIME OF EXPOSURE
1. CAST IRON IN 93% H_2SO_4
2. MILD STEEL IN 93% H_2SO_4
3. MILD STEEL IN 20% $NA_2S_2O_4$
G. PER SQ. IN. REMOVED.
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0 100 200 300 400 500 600 700 800 900 1000 1100 1200
TIME OF EXPOSURE IN HOURS.
1
2
3

FIG. 7

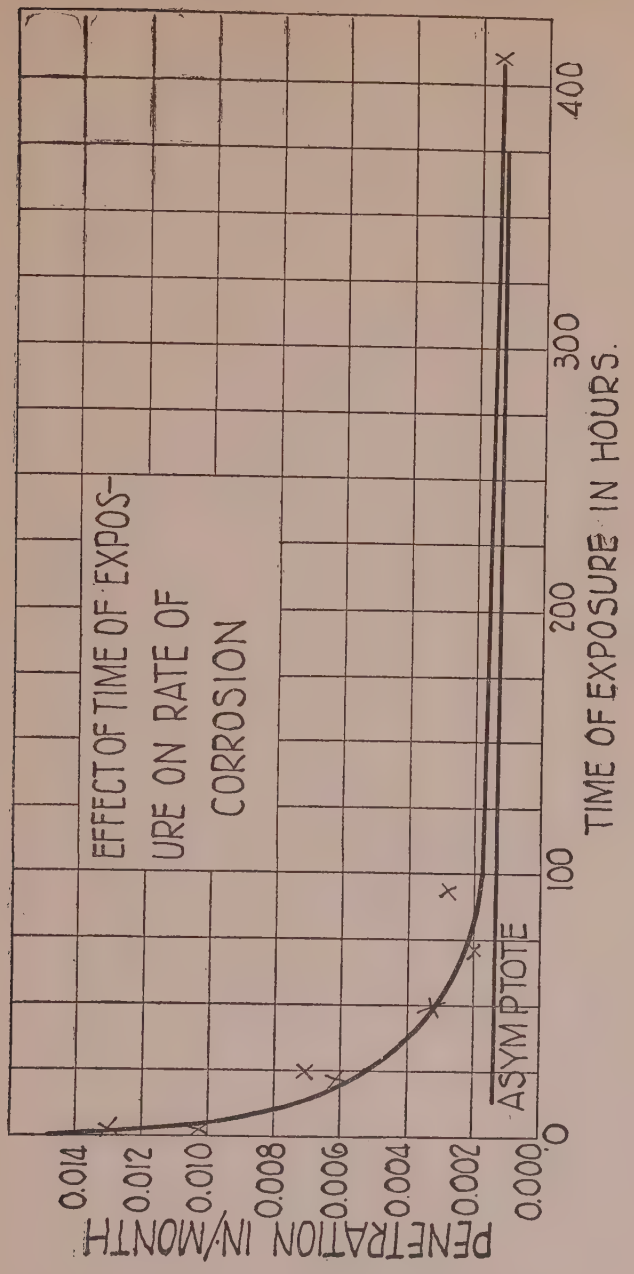
EFFECT OF TIME OF EXPOSURE ON RATE OF CORROSION
ASYMPTOTE
PENETRATION IN/MONTH
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
100
200
300
400
TIME OF EXPOSURE IN HOURS.

Fig. 8

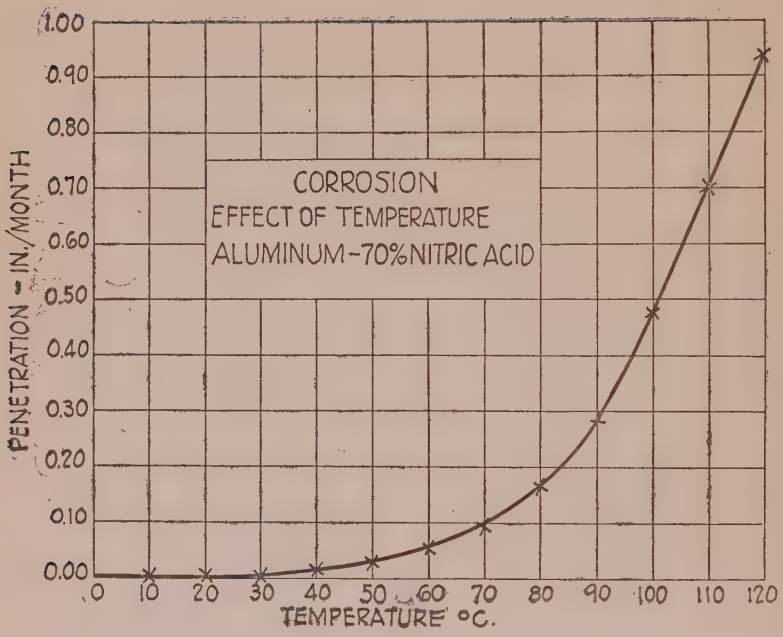
CORROSION
EFFECT OF TEMPERATURE
ALUMINUM-70% NITRIC ACID
PENETRATION - IN./MONTH
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
10
20
30
40
50
60
70
80
90
100
110
120
TEMPERATURE °C.

FIG. 9

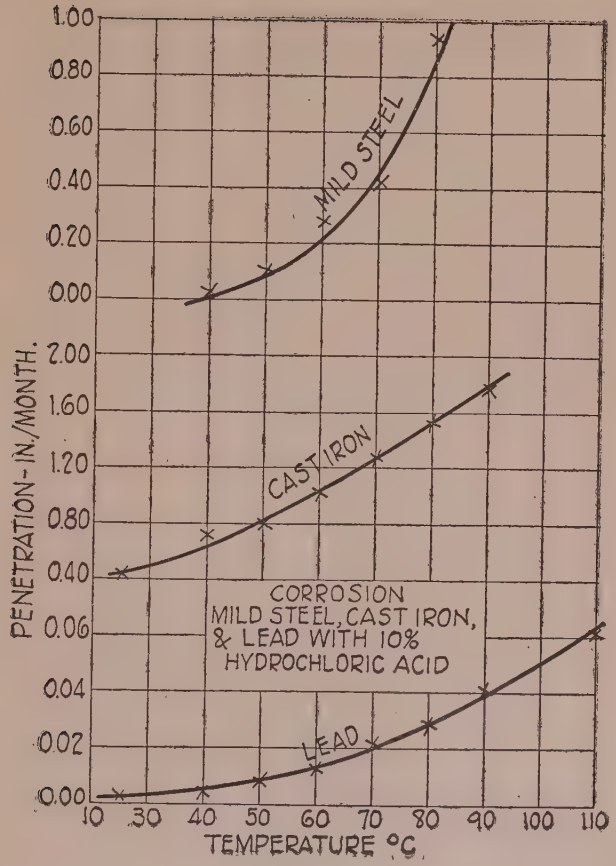
1.00
0.80
0.60
0.40
0.20
0.00
2.00
1.60
1.20
0.80
0.40
0.06
0.04
0.02
0.00
PENETRATION - IN./MONTH.
MILD STEEL
CAST IRON
LEAD
CORROSION
MILD STEEL, CAST IRON,
& LEAD WITH 10%
HYDROCHLORIC ACID
10 30 40 50 60 70 80 90 100 110
TEMPERATURE °C.

Fig. 10

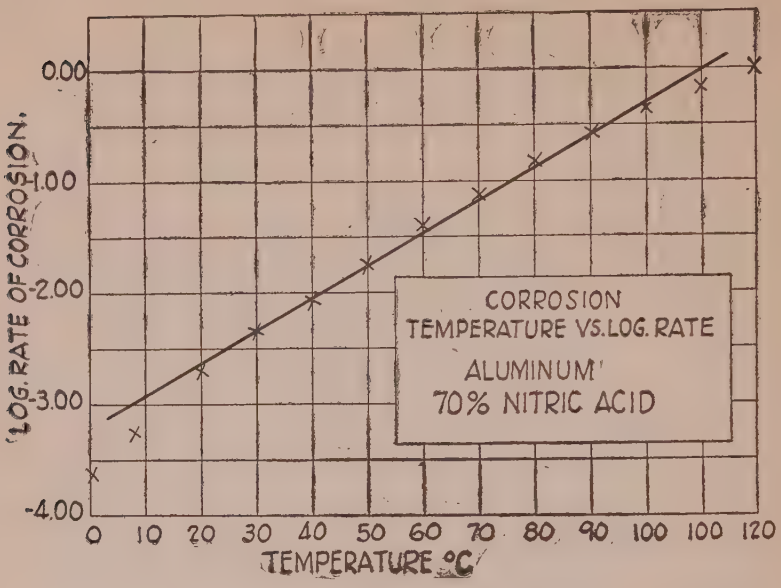
0.00
-1.00
-2.00
-3.00
-4.00
LOG. RATE OF CORROSION.
0 10 20 30 40 50 60 70 80 90 100 100 120
TEMPERATURE °C
CORROSION
TEMPERATURE VS. LOG. RATE
ALUMINUM
70% NITRIC ACID

FIG. 11

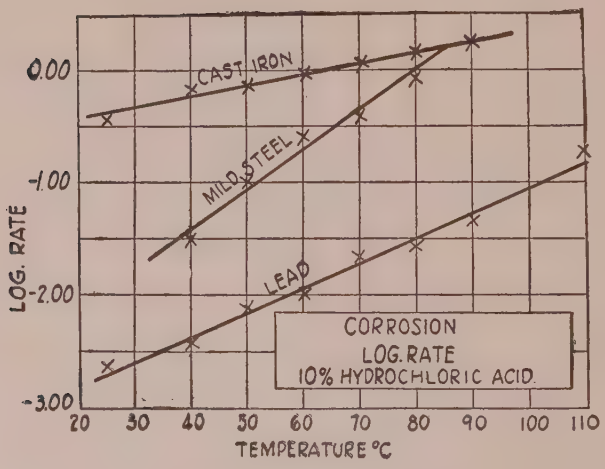
0.00
-1.00
-2.00
-3.00
LOG. RATE
CAST IRON
MILD STEEL
LEAD
20 30 40 50 60 70 80 90 100 110
TEMPERATURE °C
CORROSION
LOG. RATE
10% HYDROCHLORIC ACID

FIG. 12

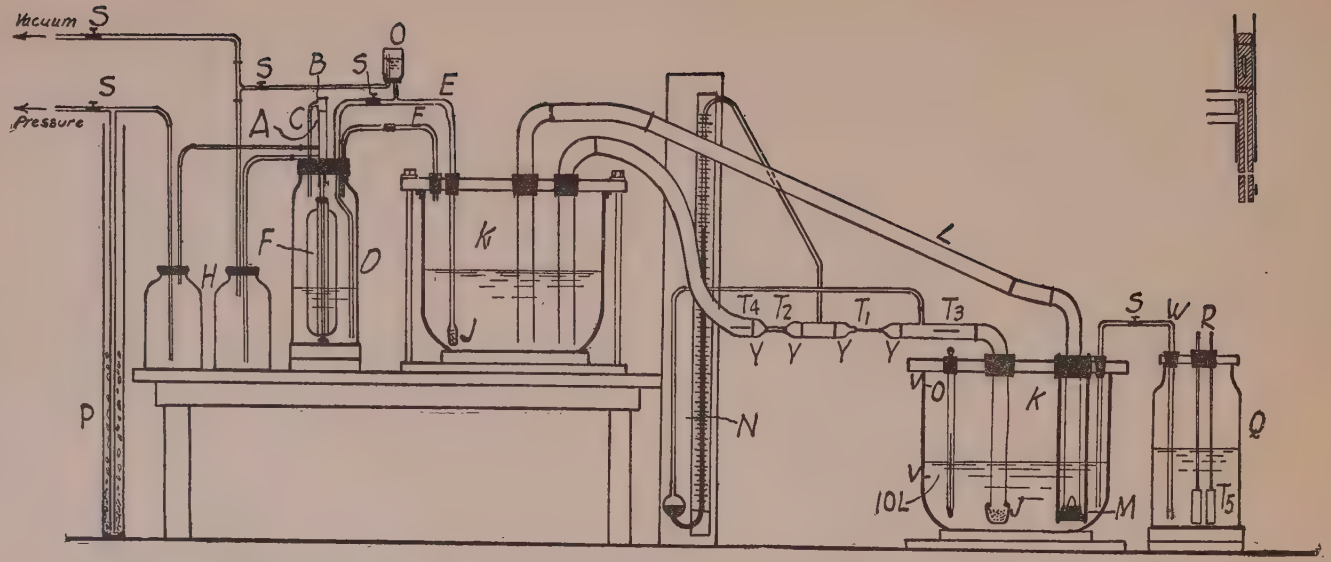

FIG. 13. Apparatus for corrosion tests under velocity conditions (0–2,000 ft./min.). *A*, air valve; *B*, air valve oil cup; *C*, air valve pressure equalization tube; *D*, float chamber; *E*, siphon; *F*, glass float; *G*, air tube; *H*, traps; *J*, glass wool filter; *K*, corrosive liquid containers (*K*, air-tight cover); *L*, return tube for corrosive liquid; *M*, glass and rubber check valve; *N*, vacuum gauge; *O*, bottle for air removal from siphon; *P*, pressure regulator ($Hg - H_2O$); *Q*, overflow bottle; *R*, glass support hooks for test pieces; *S*, screw clamps; *V*, volume calibration (10L); *W*, siphon; *Y*, glass reducers; T_1, small diameter test-tube (high *v*); T_2, large diameter test-tube (medium *v*); T_3, test piece (low *v*, atmospheric); T_4, test piece (low *v*, vacuum); T_5, test piece (zero *v*).

MATERIALS OF CONSTRUCTION FOR CHEMICAL APPARATUS

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Read and discussed at the Wilmington Meeting, June 22, 1923

Until the latter half of the nineteenth century, designers of apparatus were influenced chiefly by two considerations; namely, material cost and material strength.

Owing to the great abundance of iron ore deposits, their easy conversion to the metal, the consequent low price for iron and steel, and their great strength, this metal has always been given first consideration when construction was contemplated. On the other hand, experience has shown that iron and steel are not permanent, even when well protected from atmospheric or other corrosive conditions. In spite of this, iron and steel have held their own, and are to-day the principal materials of construction.

With the development of the chemical industry, it became necessary to manufacture large quantities of sulfuric acid. Lead was naturally adopted for construction, and, although its strength was decidedly deficient, it was much more resistant to corrosion than iron, and gradually assumed its place as "the acid-resistant metal."

These two metals were used for many decades before research and experimentation indicated that better metals and alloys could be used for acid resistant work. In the latter part of the nineteenth century the quest for new materials of construction began in earnest, owing to the great commercial development of the chemical industries during that period. Various brasses and bronzes were used for small parts, and copper and silver were used extensively in apparatus for the manufacture of dye intermediates, dye products and pharmaceuticals. Nevertheless, the higher cost of the latter metals restricted their use to a large extent, and iron, steel and lead still remained as the principal materials of construction.

Shortly before the recent war broke out, the manufacture of special alloys for resistance to high temperatures and chemically

corrosive conditions had gained a solid footing and the rapid progress which was made during war times has entirely changed not only the complexion of the field of structural materials, but also the attitude of the engineer in his selection of these materials. There are alloys available at prices ranging from 20 cents to $10.00 per lb. They range from simple binary alloys to complex mixtures containing as many as twelve different metals. The engineer must now govern his selection of materials not on the initial cost, but he must give consideration to the following points:

1. What is the service-life of the metal or alloy under given conditions?
2. How does the depreciation cost compare with the initial cost?
3. Can parts be replaced without long delays?
4. Will the metal or alloy have a harmful effect upon the materials being manufactured?

Aside from the alloys, it should be mentioned that the pure metals are being used to a large extent under conditions where they are peculiarly fitted to resist a certain corrosive agent. The more important of these are copper, aluminum and nickel. Recent developments in the metallurgy and working of refined aluminum and nickel have made them promising competitors of some of the alloys and, in certain cases, of enamelled ware.

Selection of Materials for Specific Corrosive Conditions

The engineer who is about to select the various materials with which to construct a plant must not only consider the initial cost of the material but must consider the rate of corrosion as well. The ultimate aim is to obtain from a material the maximum service per dollar expended and this resolves itself into determining the cost per time-unit of service. Where a cheap material which corrodes more or less readily is selected, the products of corrosion must not be objectionable in the product which is being manufactured. The replacement and repair costs must also be considered when selecting a material of this sort. The advantage usually lies, however, with the material which does not corrode so quickly and which costs more. The installation is more permanent; the chances of contaminating the manufactured product are not so great; and the replacement costs are lower.

The following list of materials which are resistant to specific corrosive conditions, has been compiled principally from the records of the duPont Co. Many arbitrary tests were made upon various materials at the several plants and, where valuable conclusions could be drawn from the results, they have been included here. The larger portion of conclusions have been drawn from standard corrosion tests which were performed by the Jackson Laboratory of the duPont Co. It may be well to say here that these conclusions have taken material cost into consideration in some cases but since the resistance to corrosion is the more difficult to determine, it has been considered alone in the majority of instances.

Several of the relatively new acid-resisting alloys which have appeared on the market, and for which merit is claimed, have not yet been tested and cannot, therefore, be rated in comparison with materials whose resistance to corrosion is already known for specific conditions.

It should be kept in mind that prospective apparatus should be designed wherever possible from the same material or, at least, the same material should be used in all parts of the equipment which are exposed to corrosive conditions. Where two varieties of iron or steel are to be used and a certain amount of electrolytic corrosion is expected, the metals should be tested for polarity while exposed to the corrosive reagent in order that the electronegative variety may be used for the container. Observance of this detail is not of great importance when dealing with cast iron and steel since practice has already determined the proper disposal of these metals, but where the equipment is to be of "all steel" or steel and wrought iron, a preliminary test for polarity and potential difference is occasionally a good investment where unusual corrosive mixtures are to be handled.

Acids

Acetic Acid.—Aluminum is gradually replacing copper in the construction of apparatus for acetic acid work. Copper still remains the most desirable material for use in the distillation of crude acetic acid owing to the presence of formic acid which has a very destructive action on aluminum. The presence of even ½ of 1 per cent of formic acid in crude acetic acid from acetate of lime will destroy aluminum equipment in a very short time. The

lower concentrations of pure acetic acid—i.e. from 1 per cent to 10 per cent—do slightly corrode aluminum but this is usually not considered serious enough to prevent its use. Acetic acid from an aluminum still is uncontaminated with metallic impurities even when air is present in the still. Copper gives satisfactory service only after all air has been washed from the system. The distillate is colored with copper salts and must usually be re-distilled. If precautions are not taken to prevent the surging of air in and out of the copper vent, this portion will also corrode.

Aluminum is therefore recommended for the concentration of pure acetic acid, separation of acetic from the higher homologues, and for condensing and cooling coils when the cooling water is neutral to litmus. Slightly alkaline cooling water tends to cause a pitting action which will destroy an aluminum coil within a very few weeks.

Duriron resists the corrosive action of acetic acid very well. It is rarely recommended for this work, however, since the apparatus is unwieldy, liable to fracture and possesses but little intrinsic value.

Nickel has given satisfactory service with acetic acid but has been restricted in use during the past, owing to the fact that it could be obtained only in the cast form. The castings were usually very porous. Now that nickel may be fabricated in the same manner as copper or sheet steel, it will undoubtedly be given serious consideration along with aluminum and copper.

Silver is occasionally used for containers and for condensing coils in acetylation and acetic acid reactions, particularly those for the production of fine chemicals in which contamination must be avoided.

The following materials are to be recommended for use with acetic acid. (1) For storage of weak acid—up to 10 per cent concentration—wood or hard rubber lined tanks should be used for large quantities. Earthenware or glass may be used for small containers. (2) For commercial acetic acid (containing a small percentage of formic acid), wood for storage, copper for reaction vessels and hard rubber or copper alloys for pumps, containers or carriers. In the latter case, the copper will be slightly attacked by the acid and where necessary, the color may be removed by precipitation with potassium or sodium ferrocyanide. (3) For glacial acetic acid reaction vessels, aluminum, nickel, copper and lead, respectively, aluminum being most resistant, and for pumps, storage and carriers, aluminum or hard rubber. The use of wood is both

expensive and unsatisfactory when used as carriers, since the wood not only imparts an objectionable color to the glacial acid but the latter causes the wood to shrink and deteriorate with the result that leakage soon occurs. Experience has shown that the cost of frequent replacement and leakage losses outweighs the cheapness of wood as a material for containers, and the present tendency is undoubtedly toward the use of aluminum or hard rubber-lined carriers for inter-plant and intra-plant shipments. (4) Aluminum should be used for acetic anhydride containers, although steel is generally used for this purpose. Serious leakage losses have been experienced with steel, however, and aluminum is considered to be safer.

Chloracetic Acid.—This acid readily corrodes most of the common materials of construction. Nickel has been found to stand up better than the other metals, although lead may be used in parts of chloracetic equipment.

Fatty Acids.—Propionic, butyric, Brown Acid, strong-after-glacial, etc., may be handled in the same materials as acetic acid, the same order in the choice of materials being observed. Formic acid is an exception to the general rule.

Formic Acid.—Bronze resists 85 per cent formic acid better than any metal so far tried. Copper resists this acid fairly well and much better than any of the other metals except nickel, which is said to show equal resistance with copper. Iron is readily attacked and aluminum dissolves very rapidly once the oxide coating is broken. Copper or nickel are, therefore, the metals which should be selected for this work. If riveted sheet bronze construction can be procured, it should last about twice as long as copper.

Hydrochloric Acid of low concentration is practically never handled in metallic equipment. Stoneware, glass, hard rubber or wood are always used, the selection depending upon the operation for which the acid is to be used. Wood is selected where large scale operations are being carried on at elevated temperatures, hard rubber is selected for piping, valves and pumps, glass being used only for pulsometer lines, and stoneware for parts of the hydrochloric acid plant itself. Special hard lead is sometimes used for reaction vessels in small scale operation.

Enamelled equipment has been, in many instances, the only resource of the chemical engineer in carrying out an operation in which hydrochloric acid was used or evolved. Experience has

shown this type of equipment to be an expensive investment and only warranted when nothing else will do.

At present, concentrated hydrochloric acid is handled in stoneware, hard rubber, glass and bitumen. Stoneware is used principally as pulsometer reservoirs and for storage of two or more carboys of acid at a time for some particular operation. Hard rubber is used for pumps, acid lines, valves fittings, etc., and for lining steel tanks and tank cars for the transportation of this acid. It should not be used, however, if the acid is likely to be contaminated with benzene, as may sometimes happen. Raw rubber is used for lining large wooden storage tubs and is known to give excellent service. Glass is used principally in the form of enamelled apparatus. Bitumen resists hydrochloric acid very well and has been used in the form of Positive Seal Cement for lining the wooden tanks of the old type hydrochloric acid tank car. Coal tar pitch appears to be almost as resistant as the asphaltic material but is not to be recommended, since it cracks and checks during cold weather and flows in warm weather. Moreover, it does not possess enough elasticity to prevent it from cracking or chipping off when suddenly stressed. Of the above materials, however, enamelled equipment is the most generally used although every effort is being made to develop a more serviceable substitute.

A special grade of Tantiron is claimed to be resistant to hydrochloric acid but tests which have been made on this alloy have shown that it has very little, if any, advantage over the ordinary grade of ferrosilicon alloys.

Hydrochloric acid vapors may be safely handled in iron if their temperature is above the dew point, otherwise, earthenware should be used. Lead is frequently employed for vapors which are allowed to escape to the open air from reaction vessels, and wood fume stacks are used to carry off hydrochloric acid vapors from wooden tubs. Dry hydrogen chloride may be handled safely in iron pipe and iron tanks and is usually stored in a gasometer in which concentrated sulfuric acid is used as the sealing liquid.

Hydrofluoric Acid is not used to any great extent on a large scale but it is interesting to know, however, than 60 per cent HF may be safely shipped in steel drums which have previously been passivified as described briefly below. The steel drums are filled with 58 per cent hydrofluoric acid and kept at 80° F. for 48 hours, then at 140° F. for 7 hours, allowing any gases to escape through

a ventilated bung. A protective adherent crust is formed which allows drums to be used in this service until worn out mechanically. The passivifying treatment is, of course, repeated periodically to preserve the protective coating. The same passivifying acid may be used over and over again until it has to be strengthened. These drums should be used only for shipping hydrofluoric acid and should never be washed out with water.

Lactic Acid.—The same general precautions should be observed in handling lactic acid as those described under acetic acid. It is perhaps more important that lactic acid be handled in aluminum than acetic, since the purer grades are used for edible purposes, and should contain no poisonous impurities. In the past, it has been standard practice to ship this acid in oak barrels, since the greater part of it was used in the tanning industry, but when the pure grade is shipped or stored, aluminum is the logical material for a container.

Mixed Acid.—Practically all of the useful mixed acids can be safely handled in wrought iron or mild steel. Few, if any, of them contain more than 20 per cent water and practically all of them contain 15 per cent or more of sulfuric acid. The principal danger involved in handling mixed acids is from their avidity for moisture, which brings about dilution of the films of acid in pipe lines and on the upper surfaces of storage and weigh tanks. The diluted acids destroy the container in a surprisingly short time in a manner which is called surface line attack. Every precaution should, therefore, be taken to exclude moisture, either as liquid or vapor, from the mixed acid storage system. Tanks should not be left open to the air except through a long vent and particular precautions should be exercised that all condensed water is blown out from the compressed air line before transferring acid. Mixed acids which contain 20 per cent or more of water should be stored or shipped in lead-lined tanks.

Nitric Acid is rarely if ever handled on a large scale, except in Duriron or glass, and to some extent in lead, for the stronger grades. Drum shipments of pure nitric acid whose concentration is 90 per cent or over may be made in aluminum. Practically all of the nitric acid used in the industries is handled in the form of mixed acid or is added to the particular operation as sodium nitrate. Duriron, glass, and earthenware equipment are used to a large extent in the manufacture and concentration of nitric acid, but in

some cases where the straight acid is required for an operation it is syphoned directly from a carboy. Enamelled ware has been used for operations where the addition of straight nitric acid was required, and although this type of equipment has given better service than any other, it was found to be susceptible to surface line attack, the points of failure appearing in every way to be due to a slow solvent action of the acid on the enamel itself. Where concentrated sulfuric acid is present, the straight nitric acid may be safely added to cast iron or steel equipment.

Sulfuric Acid is without doubt the most widely used acid in the chemical industry. In the various operations practically all concentrations of this acid must be handled, and consequently, the materials used in the construction of apparatus cover practically the entire field of metals, alloys, wood, glass, enamel, etc. Concentrations up to 30 per cent (cold) are handled in either lead or wood, although the use of wood for concentrations above 10–15 per cent is not considered an economical practice. Even 5 per cent sulfuric acid tends to dehydrate and shrink wood and this accounts for the constant trouble that is encountered with leaky tanks and tubs even when they have been kept well swelled with water when not in use. The only way which has been found to overcome this difficulty is to construct wooden tubs from tongued and grooved lumber. When being assembled, the dry tongues and grooves are thickly coated with some plastic composition similar to rubber cement which is relatively acid resistant. On tightening the hoops, this compound is forced into every crevice and affords an elastic cushion which offsets the shrinkage of the wood while the tub is being used in acid service. Lead is the most serviceable metal for use with sulfuric acid up to 80 per cent strength (boiling). Above 80 per cent, cast iron is the most satisfactory construction material and although the ferro-silicon alloys resist corrosion slightly better, they are not so easily adapted to complicated designs and do not stand up in active service so long as cast iron. Where the lower concentrations are to be handled and somewhat more rigid apparatus is desired than is afforded by lead, the so-called hard lead is used. Hard lead is usually slightly less resistant to sulfuric acid than pure lead but is more permanent because of its greater strength and consequently, its lesser tendency to creep and warp.

When it is desired to handle the lower concentrations of this

acid in metal equipment, a lead lining is usually resorted to. This practice, however, generally gives very poor satisfaction, owing to the exceptionally low heat transfer that is realized in jacketed equipment. For the most economical operation a lead-lined apparatus should be heated by means of an internal lead coil. Even this method is unsatisfactory in the end, however, because the coil is subject to the same drawbacks as sheet lead and in time loses its original shape and must be replaced. The anchoring of a coil of this sort presents one of two difficulties in that either a stronger and more susceptible metal, or lead must be used to support the weight of the coils. The solution of most of the above difficulties is obviously seen in the use of the so-called homogeneous lead linings. Of those which have appeared on the market from time to time, the most promising seems to be the "Zeitler" construction which has been introduced to the trade by the Oakland Copper & Brass Works of Oakland, Calif. A crimped wire screen, which has been tinned, is riveted to a tinned steel plate with copper rivets. The lead lining is then cast onto this screen in any desired thickness. The screen serves to give the lead lining a good anchorage and the tinned surfaces assure good contact and consequently optimum heat transfer, since it alloys with both the steel and the lead. This type of construction appears to have a promising future.

Cast iron is generally used for nitrators when nitrating with sodium nitrate, and although the concentration of the sulfuric acid at the start is usually from 60–65 per cent, the inner shell of the nitrator has been found to stand up in service very well when the reaction mixture was removed as soon as finished. The final acidity is usually 34–38 per cent, but this exists in the form of an almost saturated solution of sodium acid sulfate and it is believed that the large proportion of the sodium salt present tends to diminish corrosion materially.

Sulfurous Acid solutions readily attack most metals, so, for lower concentrations wood is used, redwood being much more preferable than the other varieties. Higher concentrations than 5 per cent of sulfurous acid, as such, are rarely used, but lead, bronze and copper are the metals that are generally employed for this work. Dry sulfur dioxide gas and dry liquid sulfur dioxide may be handled in iron or steel tanks or pipe lines.

Alkaline Corrosive Agents

Caustic Alkalies.—Sodium and potassium hydroxide, or mixtures of the same, differ very little in their effect upon the metals. Of the commoner metals, those which resist caustic alkali well enough to be used for chemical apparatus are nickel, monel metal, copper, wrought iron, low silicon cast iron and mild steel, nickel being the most resistant. Nickel is widely used in the laboratory for caustic fusions but on account of its relatively high cost as compared with iron, it has not been considered for use on a large scale. Copper is not often employed because of the impurities it introduces into caustic reactions and the difficulty of their removal in ordinary operations, particularly if the caustic be used in low concentrations. Considering all factors, copper is but little better than iron or steel for reactions where the concentration of the caustic is below 37°–40° Bé., and, if the operation has not been standardized to that extent which would warrant the expenditure for riveted nickel equipment, low silicon cast iron or cast 5 per cent nickel steel should be used. Iron stands up quite satisfactorily in very dilute solutions of caustic, but the presence of the latter facilitates atmospheric corrosion somewhat.

Although strong caustic solutions are very destructive to wood, it is sometimes necessary to use it when these solutions are to be acidified and metallic impurities would be harmful to the product. In such cases, e.g., caustic fusions of certain sulfonic acids, the autoclave charge should be cooled as far as practicable before blowing to wooden tubs and neutralization should begin immediately. Whereas strong caustic solutions tend to disintegrate wood by dehydration and partial solution, the weaker solutions accomplish the same result by hydrolysis and partial solution, and for this reason lead linings are sometimes used and have been found to stand up very well in less than 10 per cent caustic solutions if the temperature is not allowed to exceed 90° C. At ordinary temperatures lead satisfactorily resists concentrations up to 25–30 per cent. Lead is susceptible to corrosion by caustic with the formation of soluble salts, but for the reaction to assume any noticeable proportions, the concentration of the caustic must be above 10–15 per cent, the temperature must be elevated, and usually an oxidizing agent must be present.

Strong caustic and soda ash solutions cause rapid deterioration of filter cloths, particularly when the latter are subjected to high temperatures for prolonged periods. It is occasionally more economical in the end to use metallic filter cloths of monel metal if the precipitate is not of a semi-colloidal nature. If the liquors contain sulfides, however, monel metal cloth should not be used. Cotton cloths are more economical for filtering dilute alkaline liquors.

Ammonium Hydroxide.—There are relatively few places where ammonium hydroxide, as such, is used as one of the principal components of a reaction. Its occurrence is usually incidental to a slight decomposition of amino compounds during the caustic fusion of an organic amino sulfonic acid, to the becoming alkaline of an iron reduction of a nitro hydrocarbon, or as a by-product in such operations as the following: (1) Destructive distillation of coal; (2) hydrolysis of an amino sulfonic acid by means of the sulfite ester reaction; (3) hydrolysis of amino sulfonic acids at high temperatures and pressures with dilute sulfuric acids; (4) reduction of the residual nitric acid in diluted nitration masses of naphthalene sulfonic acids, with iron, etc. In the latter two cases, the ammonia does not occur as such but combines with the excess acid. With the exception of the first case, which is one of the principal sources of supply, little effort is at present being made to recover the ammonia.

The more common cases where ammonia is used as one of the principal constituents of the reaction are: (1) manufacture of ammonium nitrate from ammonia liquors and recovered nitric acid; (2) digestion under pressure of an aromatic nitrochlor hydrocarbon with concentrated ammonia to form the corresponding nitroamino compound; and (3) the digestion under pressure with a naphthol, e.g., beta-naphthol, to form the corresponding beta-naphthylamine. In each of the three above cases, special conditions prevail which determine the nature of the equipment which may be used.

In the first case, the ammonia liquors are stored in closed steel tanks, particular attention being exercised that as few connections as possible are made above the liquid level because moist ammonia vapors have been found to be more corrosive than the liquors. During the neutralization, a brick-lined wooden tub, placed underground, is used.

The second case is typical of a condition where the nitro group acts as an oxidizing agent and corrosion takes place in spite of the exclusion of all air from the autoclave in which such a reaction is carried out. If the product which is being manufactured is of such a nature that it must be free from small traces of metallic impurities and is very difficult to purify, enamelled equipment must be used. Even the acid resistant metals are susceptible to this type of corrosion and cannot be used without contaminating the product. The same is true when purifying delicately colored products by recrystallization from ammonium hydroxide solutions. If air is present, it usually takes part in the reaction and the corrosion products which are formed result in an impure product. Thus, when dealing with these conditions, it should be remembered that products whose purity is judged by the clearness of color and which are difficult to purify, should be handled in enamelled equipment. Aluminum and tin are said to be unaffected by ammonia alone even in the presence of air, but the former cannot often be used, since the presence of only small amounts of alkali salts form alkali hydroxides and rapidly attack the metal.

The third case is typical of a reaction whereby a product is obtained that is readily purified and, in fact, must usually be purified before it can be used for subsequent operations. In this instance, iron or steel equipment give entirely satisfactory service. There being no oxidizing agent present besides air (the major part of which is washed out of the autoclave by volatilization of the ammonia) there is very little corrosion and the crude product is only slightly contaminated with iron, which remains behind in the residue when the product is sublimed or distilled.

Where ammonia is evolved as a by-product, it is usually handled in lead lines if the vapors are moist. Iron lines may be used for the dry ammonia gas, liquid ammonia and moist ammonia vapors if, in the latter case, the presence of iron rust is not objectionable in the condensate.

Copper should never be used where it will be exposed to ammonia. It is easily attacked either in the form of pure copper or its alloys.

Salts and Other Compounds

Notwithstanding the fact that a great deal of effort has been expended on the the collection of data with regard to the corrosive

properties of neutral and other salts, there is still a great deal to be learned. Only the most pressing problems have been investigated, particularly those which involved a very appreciable corrosion rate, and those salts or compounds which do not corrode iron or lead very seriously have received but little attention. As a result, the data which follow must, in most cases, be considered as more or less arbitrary since they were sometimes gathered in hurried tests which were made more with the object of determining whether a certain metal would be satisfactory or possible, rather than which metal of those available would give the most economical service. It is quite possible that in some instances better materials may be found.

Aluminum Chloride is used in several condensation reactions, notably the Friedel and Craft's reaction. It is, of course, used as the anhydrous salt and, during the reaction, hydrogen chloride is evolved. If the reaction is anhydrous, as should always be the case, it may be carried out in iron or steel equipment without danger. Precautions should be exercised, however, that when running intermittently, the equipment be flushed out after the last run of a series with dry air or some anhydrous volatile solvent followed by air, in order to remove hydrogen chloride. If these precautions are not taken, the deliquescent vapors will attract moisture from the atmosphere and hydrochloric acid will condense upon the vent line and sides of the reaction vessel. A thorough cleaning will then be necessary before the next run is made in order to avoid contamination of the product with iron salts.

Aluminum Sulfate (Alum) tends to hydrolyse with the formation of sulfuric acid which readily attacks iron. Lead is recommended for piping and hard lead containing about 9–10 per cent of antimony is advised for rigid equipment.

Ammonium Chloride Solutions up to 10 per cent strength may be handled in lead.

Ammonium Nitrate, when dry, is stored in iron barrels. The moist salt corrodes the barrel and "sets" into a solid lump which is difficult to remove. Copper, monel metal, the brasses and bronzes should not come in contact with the salt during its manufacture or its incorporation in any of the explosives, for although the copper corrosion products are not known to form sensitive compounds with the ordinary explosives or explosive mixtures, they do tend

to lower the ignition point of such mixtures as amatol. Tin, on the other hand, is thought to form sensitive salts with ammonium nitrate and should, therefore, be avoided. Wood and aluminum are the two materials which are usually recommended for mixing ammonium nitrate with other explosive ingredients.

The evaporation of ammonium nitrate liquors at one time presented a very serious problem, owing to hydrolysis of the liquor to ammonia and nitric acid, accumulation of the latter and electrolytic corrosion between the cast iron vessel and the wrought iron steam coils. These difficulties were overcome by the use of an anti-acid to neutralize the excess acid and by thoroughly insulating the steam coils from the rest of the machine, and finally, all parts of the machine from the ground. This was accomplished by means of non-conductor gaskets and bolts equipped with mica sleeves and washers.

Aniline and Other Amino Hydrocarbons have a peculiar corrosive action on copper, brasses, bronzes, aluminum, magnesium (and perhaps some of the other metals) owing to the displacement of one or more hydrogen atoms in the amino group by the metal itself. This reaction is usually considered to be a high temperature reaction, although instances are known where 3 per cent solutions of aniline in hydrocarbons have readily attacked copper at ordinary temperatures.

Antimony Chlorides are generally used as chlorinating agents. The tri-chloride crystals are chlorinated in an enamelled or lead lined vessel and pentachloride, which is a liquid, is used in the same manner as the phosphorus chlorides. These reagents are very corrosive and have been known to attack enamelled equipment in a short time. The reactions are anhydrous and hydrogen chloride is usually evolved. Enamelled equipment is preferable on account of its cleanliness, but lead is perhaps more economical.

Benzaldehyde corrodes zinc noticeably. In this case an arbitrary test was made with several metals, zinc giving better results than the others. It seems probable, however, that a more useful and adaptable metal could be found if necessary.

Benzoic Acid Vapors corrode the commoner metals quite readily at a high temperature (250° C.). Nickel, monel metal and copper gave the most satisfactory results, nickel being best. Monel metal (hardness = 20) corrodes about 50 per cent more rapidly and

copper corrodes about three and a half times as rapidly. Preference should be given to nickel notwithstanding the cost price differential.

Bromine, like the other halogens, may be stored in iron when kept cool and absolutely dry. When used in chemical equipment, even when the reaction is supposedly an anhydrous one, the bromine attacks iron locally. A remedy which is frequently used to good effect is to allow the bromine to flow or react in a porcelain or enamelled dish. The hydrobromic acid which is formed will not affect the iron equipment if proper precautions are taken to keep out moisture. Enamelled equipment should always be used if the reaction is not anhydrous.

Chlorbenzol may be safely handled in iron containers if it has been freed from residual hydrochloric acid.

Chlorine, when dry and gaseous, may be handled in iron or steel equipment and conveyed in iron lines. When used in chlorinations under anhydrous conditions, it should be remembered that hydrochloric acid is evolved and should be removed between operations. Where moisture is present, enamelled or ferro silicon equipment should be used. Lead has occasionally been used for chlorination operations when a substitute for iron or steel was desired.

Ferric Chloride is very corrosive to iron, nickel, copper or monel metal equipment; in fact, few metals satisfactorily resist it. Enamelled apparatus is claimed to be the most economical equipment.

Formaldehyde may be handled in iron equipment with neither appreciable corrosion of the iron nor pollution of the formaldehyde.

Iodine.—The same remarks apply to iodine as those found under bromine.

Nitro-Chlor-Benzol.—A test has shown that brass and copper resist moist boiling mono-nitro-chlor-benzol only fairly well, although the corrosion rates are not so high as to preclude the use of these metals.

Nitro-Phenol (Para).—Copper resists a saturated boiling solution of p-nitro-phenol very satisfactorily. Lead indicated poor resistance.

1:4 and 1:5 Oxy Acids.—The conditions which arise in the manufacture of these two acids (Neville and Winther's, and Oxy L Acids, respectively) require resistance to caustic soda, sodium bisulfite, ammonia, hydrochloric acid and sulfur dioxide (moist). The only cheap metal which seemed to satisfy these conditions

fairly well was lead, although, in service, it was found to succumb rather quickly. No completely satisfactory substitute has been found as yet. The corrosive conditions are so incompatible for any one alloy or metal that perhaps the ultimate solution will be the use of two separate vessels with adequate facilities for quick transfer from one vessel to the other. One vessel would be designed to resist the acid group of conditions, and the other the caustic and ammonia group.

Phosphorus Chlorides.—The various chlorides of phosphorus which are used as chlorinating agents owe their reputation as extremely corrosive substances to the fact that hydrogen chloride is usually evolved during the chlorination reaction. When the conditions which surround the reaction are anhydrous, iron and steel equipment may be used with safety but it should be pointed out here that the same care and and precautions should be taken as those described under the paragraph on Aluminum Chloride. If these precautions are not taken, it will be necessary to resort to lead lined or enamelled equipment. The nature of the reaction requires that conditions be anhydrous in order to utilize all of the available phosphorus chloride but conditions sometimes arise where a small amount of moisture is present at the beginning of the reaction and in such instances hydrochloric acid is always formed by hydrolysis of the phosphorus compound. The temperature of the equipment then is the deciding factor, for if it is lower than the dewpoint corresponding to the concentration of the hydrochloric acid, active corrosion will take place. Thus, the essential consideration in deciding upon equipment to handle this type of reaction is whether or not anhydrous conditions can be maintained. If so, iron and steel equipment may be used when the proper precautions are taken. Otherwise enamel or lead lined apparatus must be resorted to.

Polysulfide Solutions give very little trouble and up to the present time iron equipment has given satisfactory service except for the first few runs. Iron is found in the product when making the first few fusions in a new machine, but it is believed that the formation of a protective coating of possibly some iron sulfide makes the equipment passive to further corrosion.

Salicylic Acid.—When moist salicylic acid vapors come in contact with iron a purple decomposition product is formed which

colors the final product and makes it unfit for the market. The does not seem to be affected by moist vapors.

Sodium Sulphite in aqueous solution readily attacks iron. Lead lined wooden tanks are usually used to handle this material. Where the sodium bisulfite is used and where the fused salt is used as a softening agent with strong sulfuric acid in lieu of oleum, iron is a satisfactory material for equipment.

Sodium Chlorate solutions slowly attack iron, particularly when conditions are favorable for electrolysis. Lead may be used for tank linings where necessary. Copper, bronzes, brasses and monel metal all withstand boiling 10 per cent solutions of this salt satisfactorily.

Sodium Hydrosulfite as such in neutral solution does not corrode iron very rapidly. The use of this metal is usually prescribed, however, on account of the danger of contaminating the hydrosulfite. Both iron and aluminum are usually avoided and lead, although fairly satisfactory, is not often used for permanent installations. The metals which have been found to resist this reagent and to assure cleanliness of the product are tin, nickel and monel metal. They not only withstand corrosion by solutions and suspensions of the salt itself, but also the other reagents that are met with in the process of manufacture. This does not include, of course, the first step in the process. There seems to have been a considerable difference of opinion with regard to the material for the digester and where enameled equipment was actually used for this operation, it is thought that iron or steel would give equally good service, and any small amounts of iron that dissolved out would be removed during the preliminary filtration.

Sodium Hypochlorite solutions up to 20 per cent concentration may be safely handled in iron or steel equipment. Copper is also satisfactory. Lead is not recommended.

Sodium Sulfate solutions of 10 per cent concentration at the boiling temperature can be handled in iron or lead. Copper is also satisfactory. This salt has been found valuable in decreasing the corrosion of the lead linings in wooden tanks which are used to collect spent nitrating acids and wash waters. It was found that a 10 per cent salt-cake solution in the tank reduced the corrosion to a little over 3 per cent of the former rate in one case tested. The spent acid in this case contained about 4 per cent HNO_3 and 2 per cent H_2SO_4.

Sodium Sulfide attacks cast iron only very slowly and it may be said that the atmospheric influences here are more effective than those exerted by the sodium sulfide. Where an iron-free product is desired, it is not necessary to avoid iron equipment but frequently to remove rust from equipment which has been standing idle, before using it. Monel metal is particularly susceptible to sulfides and should not be used as tank linings or as metallic filter cloth where solutions will come in contact with it. Lead resists sodium sulfide solutions fairly well.

Sodium Sulfite is not usually handled in iron or steel. Solutions up to 20 per cent concentration at 25° C. may be handled in lead and monel metal. Redwood has also been found to resist solutions of this salt satisfactorily.

Sodium Thiosulfate.—A test has shown that monel metal resists a 10 per cent solution of this salt at 80° C.

Superheated or High Pressure Steam.—Iron valves are not recommended for permanent installations owing to the susceptibility to corrosion at the high temperatures involved. Bronzes and the ordinary brasses are not suitable on account of the tendency of the valve disks or gates to warp. Experience has shown that nickel and nickel alloys withstand the corrosive and erosive conditions of high temperature steam much better than any other common metal or alloy, and moreover, are not subject to warping. For these reasons, the disks, gates, valve seats and sometimes the whole valve is constructed of nickel or some high nickel alloy, such as Aterite, monel metal, etc.

Special Metals and Equipment

Special alloys and equipment have appeared in the chemical equipment field from time to time and it is often difficult to determine whether the optimistic claims which are made for these materials will be fulfilled in actual practice. In the majority of cases manufacturers give service as well as well material and they generally advise against the use of their material if they believe the results to be obtained with it are open to question. Notwithstanding this, it is frequently a difficult problem to decide whether an advantage is to be gained in the adoption of highly corrosion-resistant equipment at high cost or in the adoption of less resistant equipment at the usual cost.

Six factors stand out above others in making the decision. They are: (1) Permanence of the process; (2) Long life of equipment, or in other words, cost per unit of time while equipment is in service; (3) Contamination of manufactured product with products of corrosion; (4) Replacement cost including replacement repairs, as well as time and profits lost by shut-down; (5) Efficiency of machine with respect to heat transfer, etc.; and (6) Intrinsic value of structural materials when the equipment is scrapped. They should all be given consideration, particularly if the equipment is not to be temporary.

Alloy Steels are often used as corrosion resistant materials in the chemical industry. The use of stainless steel, which is an 11–14 per cent chromium steel, is limited to cutlery, surgical instruments and sheets for lining equipment used in the manufacture of fruit juices. Some of the claims made for this alloy have been misleading, for, although the metal resists atmospheric corrosion even at moderately high temperatures, as well as attack by acid fruit juices, it is susceptible to attack by mineral acids and under certain conditions corrodes almost as readily as steel. It is of interest to know that when rust once begins to form on stainless steel and is not removed, the alloy corrodes in the atmosphere much the same as does ordinary steel.

Nickel Steels are of interest for two reasons. Caustic fusions at high temperatures are known to cause embrittlement of ordinary steel and experience seems to have shown that addition of 5 per cent nickel to the steel tends to prevent this difficulty. The second valuable use for nickel steel is based upon the discovery of Guillaume in 1898. He found that the addition of nickel to steel had a profound effect upon its coefficient of expansion. When steel contains 23–24 per cent nickel the coefficient of expansion is almost twice that of ordinary steel. With 36–37 per cent nickel the coefficient of expansion is almost zero. The latter alloy called "Invar" is used for clock pendulums, hair springs, balance wheels for watches, measuring tapes for surveying, etc. As the percentage of nickel is increased, the coefficient rises again and at 42–46 per cent nickel a series of alloys is obtained whose expansion coefficients are very nearly the same as that of glass. These alloys are called "Platinites" and have been used as lead wires through the glass stems of electric light bulbs, wire screen for reenforced

window glass, etc. It is thought that such alloys should find use also as a base metal for enamelled equipment for, by this means the destruction of the enamel coat due to thermal expansion is avoided.

Monel Metal gives satisfactory service in contact with fused caustic soda. It cannot be recommended for use with either gaseous hydrochloric acid or its water solutions although at ordinary temperatures, dilute acid up to 2 per cent does not seem to appreciably attack this alloy and when cold, even 10 per cent HCl may be handled. Lack of experience with this material on a large scale naturally forbids definite recommendations in connection with HCl, the above data having been obtained in connection with laboratory tests. These tests have shown monel metal to be slightly attacked by formic acid but not affected by palmitic, butyric, or oleic acids. It is said to be resistant to benzoic, carbolic, citric, lactic, cold picric, salicylic, tannic and hydrocyanic acids. Chlorine has little or no effect upon this alloy. It is only slightly attacked in cold electrolyte solutions although it is not recommended in contact with other metals and an electrolyte solution. Such a combination, however, was used with success at a dye plant where monel metal set screws were used to fasten cast iron paddles on a steel shaft. There was a potential difference of 300 millivolts under conditions of the reaction, the monel metal being electro-positive. Notwithstanding the fact that the reaction was slightly acid and the temperature 100° C., no noticeable corrosion was observed.

Monel metal can be used satisfactorily in contact with hydrosulfite and the mother liquors met with in that process but tin is preferred on account of the lower cost. It stands up well in boiling 10 per cent NaCl solution, 10 per cent sodium thiosulfate solution at 80° and most concentrations of sulfuric acid up to 50 per cent at 60° C. Boiling 1 per cent to 2 per cent H_2SO_4 should not be handled in this alloy although moderate concentrations may be safely handled up to 60–80° C. Monel metal is not often used with sulfuric acid but when it is desirable to prevent appreciable amounts of metallic impurities from contaminating a product, it is sometimes preferred to lead. In connection with acetic acid work, cheaper metals that give more satisfactory results over wider ranges of temperature and concentration usually exclude monel metal from consideration.

Hard Leads.—Three different types of hard leads have appeared

on the market and only one of these, namely antimonial lead, has been a commercial success. An alloy known as Ulco lead composed of about 98 per cent lead and about 2 per cent of calcium or barium was used for a short time. While it had the hardness of antimonial lead, experience showed that the latter was preferable for most uses.

Lead-nickel alloys were not a success owing principally to foundry difficulties. The nickel did not contribute to the alloy sufficient tensile strength to allow it to compete with antimonial leads already on the market. Their resistance to corrosion is, however, greater than that shown by antimonial leads or pure lead.

The lead antimony alloys usually contain from 10–25 per cent of antimony, although that used in the chemical industries usually contains 12–13 per cent. The eutectic alloy contains 12.5 per cent of antimony. It is soft and workable, and yet has a tensile strength about three times that of pure lead. Alloys containing more than 13 per cent of antimony contain small hard grains of metallic Sb, which tend to float to the surface if the casting is cooled too slowly. These alloys are almost as resistant as lead to sulfuric acid in the cold, but are much more easily attacked by the concentrated acid at higher temperatures. They stand up well in cold hydrochloric acid at any concentration and at 100° C. up to about 18 per cent concentration without an appreciable loss. These alloys may be threaded, but with 13 per cent antimony they are easily stripped. Where threaded hard lead is desired, an 18–20 per cent alloy is used.

Copper-Zinc-Nickel Alloys.—Certain of these alloys possess very satisfactory corrosion resistance and may be classed as competitors of Monel metal when their applications are taken into consideration. The two most widely advertised of these alloys are Aterité and Meco metal, manufactured by the H. M. Aterite Co.,of New York and the Midwest Engine Co., of Indianapolis, respectively. Both of these alloys are variable in composition since they are designed for use under several different corrosive conditions. An analysis of one sample of Aterite indicated the following composition: Copper 60.6 per cent, zinc 27.3 per cent, nickel 10.8 per cent, antimony 0.4 per cent and undetermined 0.9 per cent. Meco metal is composed of approximately 50 per cent copper, 25 per cent nickel, 20 per cent zinc and 5 per cent of other metals.

These alloys are not quite so resistant to dilute HCl at low temperatures as Monel metal but are more resistant at elevated temperatures. Aterite is recommended by its manufacturers for use with superheated steam, hydrofluoric and the organic acids as well as sulfuric and sulfurous acids. It is also recommended by them for calcium hydrate, caustic soda and potash. The Aterite Co. does not recommend it for chromic, hydrochloric or nitric acids, picric acid, mixed acids or ammonium hydroxide. Meco metal is marketed at present only in the form of machinery, principally pumps for handling mine waters of 0.5 to 10 per cent acidity. Laboratory tests have indicated that there are several conditions under which Meco metal would give satisfactory service in the organic chemical industry. None of these applications has so far been given a thorough try-out under works conditions, however.

Miscellaneous Alloys.—Other alloys which have been recommended at one time or another for chemical construction are: Ceco, Hardite, Illium, Ampco, Stellite, Bario and Magnalium.

Ceco is composed principally of aluminum which is alloyed with 2–4 per cent of rare earth metals and is used as a substitute for aluminum construction. The manufacturer recommends this alloy for use in connection with acetic and nitric acids, but tests which the duPont Co. has made both in the laboratory and plant indicated that aluminum resists these acids better than the alloy. Ceco alloy probably has the advantage when construction of a pump is being considered owing to its better mechanical properties.

Hardite which was found by analysis to be composed of nickel 45 per cent, chromium 15 per cent, iron 13 per cent, silicon 10.6 per cent, copper 6 per cent, zirconium 4 per cent, molybdenum 3.45 per cent, manganese 2 per cent, and aluminum 0.95 per cent, was first introduced as a nitric acid resistant metal. Corrosion tests showed, however, that although this alloy is resistant to 30 per cent HNO_3 at room temperature or 10 per cent HNO_3 at 55–65° C. its range of usefulness was not wide enough and its susceptibility at other temperatures and acid concentrations precluded its use for general nitric acid use. Its cost in 1918 was quoted at $3.50 per pound, rather high for a structural material.

Illium is an alloy which Dr. S. W. Parr of the University of Illinois developed for use in his bomb calorimeter. It is essentially a nickel-chromium alloy and has the following composition: nickel

60.65 per cent, chromium 21.07 per cent, copper 6.42 per cent, molybdenum 4.67 per cent, tungsten 2.13 per cent, aluminum 1.09 per cent, silicon 1.04 per cent, manganese 0.98 per cent and iron 0.76 per cent; total 98.81 per cent. It is claimed to be very resistant to mineral acids but especially resistant to dilute nitric and sulfuric acids. It also gives good service when used for alkaline fusions with sodium peroxide and sodium hydroxide. Illium G of approximately the above composition costs $4.00 per pound. A second illium alloy, Illium B, consisting of 50 per cent Illium G and 50 per cent iron costs $3.50 per pound.

Ampco, which is one of the aluminum bronzes, is composed of 85.5–87.0 per cent copper, 9.7–10.9 per cent aluminum and 3.1–3.6 per cent iron and is comparable to steel in its general properties. It is a good bearing metal and like most aluminum bronzes of approximately the above composition is claimed to satisfactorily resist acetic, lactic, phosphoric and tartaric acids very well up to 50 per cent concentration at 90° C. It resists sulfuric acid up to 50 per cent in the cold very well but 35 per cent acid at 90° C. shows a slight tendency to react. Nitric and hydrochloric acids readily attack Ampco. The duPont Co. has had no experience with this alloy.

Stellite is an alloy which has become better known as a material for high speed tool steels and cutlery than as an acid resisting alloy. It is composed of approximately 75 per cent cobalt, 16.5 per cent chromium, 3–4 per cent silicon, 1–2 per cent carbon, 2 per cent iron and 1 per cent nickel. 5–10 per cent of tungsten is added when the alloy is to be used as a high speed tool steel. The cost of cobalt makes the price of this alloy too high to allow of its consideration as an acid resistant alloy.

Bario was first introduced as a platinum substitute for laboratory ware. Its composition varies but it is approximately 85.33 per cent nickel, 9 per cent tin, 4.25 per cent chromium, 1.22 per cent tungsten and 0.2 per cent silicon. Very elaborate claims were made for this alloy and but few were substantiated by actual test. Later samples were found to contain more iron than nickel although the cost was stated at $10.00 per pound. It has neither been used nor recommended for any of the duPont Co.'s work.

Magnalium and *Elektron* are very similar in composition. The former is composed of about 90.6 per cent magnesium, 9.3 per cent

aluminum and a trace of iron. The latter is imported from Germany and consists of approximately 85 per cent magnesium and 15 per cent aluminum. Their specific gravities are about two thirds that of aluminum. They are of use principally for the construction of very light machine parts that are not likely to be exposed to corrosive conditions. The mechanical properties of these alloys compare very favorably with steel in some respects.

Nickel is now obtainable in sheets and plates so that equipment may now be constructed similar to that of riveted steel. There is a promising future ahead of nickel in the chemical equipment field. The structural strength of nickel is said to be about 3½ times that of copper and about the same as that of steel. The intrinsic value of the worn out machine after a long life is high enough to finance an appreciable portion of the replacement cost. The future of nickel seems to lie, however, in the fabricated equipment field rather than in nickel castings, because of the practical impossibility of producing large castings which are non-porous.

Aluminum is the strongest metal compared with its weight in use to-day if we except the magnesium-aluminum alloys which are not applicable to chemical construction. It is of most use to the chemical industry in its purest form, since it seems to be least affected by corrosive agents when pure. It is used rather widely in the food and drug product industries as its oxide is colorless and non-poisonous. Owing to the porous and open-grained structure of its castings, it is of most use in the fabricated form.

Aluminum is recommended for acetic acid equipment except when used in connection with the crude acid containing formic acid. The pure metal resists high concentrations of nitric acid and its fumes very well, but when so used the temperature should not be allowed to rise appreciably.

When handling nitric acid solutions in aluminum it is important that they be free from H_2SO_4, HCl and NO_2.

All alkalis attack aluminum readily even at low temperatures. Ammonium hydroxide does not when pure. The presence of an alkali salt, however, would preclude aluminum from consideration owing to the formation of an alkali hydroxide. When used as cooling or condenser coils attention should be given to the cooling water. If it is alkaline, it will pit and destroy the coils in a very few weeks.

All fatty acids except formic may be safely handled in aluminum, as may also phenol, cresol, alpha and beta naphthol, as well as the aliphatic and aromatic alcohols, but it should be remembered that anhydrous substances usually have a deleterious effect, particularly in the case of phenolic and alcoholic products. Seligman and Williams[1] state that only a small amount of water—as little as 0.04 per cent in some cases—inhibits the corrosive action entirely.

Amino hydrocarbons such as aniline, toluidine, naphthylamine, etc., react with aluminum in the same manner as they do with copper. These reactions are described under German Patent No. 287,601.[2]

Care should be taken that broken thermometers or mercury be kept away from aluminum equipment because mercury initiates a very strong pitting action locally.

Heat-Resisting Alloys.—The better known alloys which are used for heat-resisting purposes are: Nichrome, Q-alloy, Pyroloy and Thermalloy. It is, however, inadvisable to recommend any one heat-resisting alloy as a panacea for all heat corrosion ailments. Mr. Frank A. Fahrenwald, who has given considerable study to this field, has very ably presented the considerations involved.[3] The du-Pont Co. has tested many of these alloys and has found one to be superior in one installation and another elsewhere. The conditions surrounding the various experiments are, however, too involved to allow of their discussion here. Actual tests of the various heat-resisting alloys should be made under operating conditions, giving attention to their mechanical as well as their corrosion-resisting properties.

Enamelled Equipment has never been able to banish the feeling among chemical engineers that it is an unwelcome stranger but one whom we must recognize when necessary. This type of equipment combines the strength of iron or steel with the acid-resistant qualities of glass, but even so, the shortcomings of this type of equipment outweigh its advantages. It is fragile when subjected to stress, is relatively easily chipped when subjected to rigorous temperature or pressure conditions, the initial cost is high, the length of service is always uncertain and unfortunately the slightest break

[1] J. Soc. Chem. Ind., 37, 159T (1918).

[2] Friedlander, 12, 123.

[3] Chem. Met. Eng. 28, 680 (1923).

in the enamel coating destroys the value of the whole equipment for the particular purpose for which it is being used.

No method of applying the enamel coating will allow it to withstand the shock of a dropped monkey-wrench or other tool. Improvement is possible, however, both in the manufacture and use of this equipment. A good many of us have seen the effects of high pressure and high temperature operation on enamelled equipment and I believe we will agree that the use of an insert is generally advisable for this type of service. By this means the pressure is the same on both the inside and outside of the enamelled container, it being transmitted by means of the fusible alloy bath which is generally used. The temperature differential between coefficients of expansion of the enamel coating and the base metal is our most important difficulty. So far, correction of this difficulty has been attempted by adjusting the coefficient of expansion of the enamel to the iron with possibly some sacrifice in its quality. The more logical method of adapting this type of equipment to the rigorous requirements of the chemical industry would seem to be just the opposite. Undoubtedly, the cost would be increased by using a base metal composition similar to Platinite—previously described under Nickel—but we could determine the enamel composition which is most resistant and then adapt the base metal of the insert to conform with the required expansion coefficient of the enamel.

Enamelled equipment is generally used in connection with reactions evolving hydrogen chloride in the presence of water or water vapor. Other corrosive reactions such as chlorinations, brominations, alkylations, condensations with phosgene, aluminum chloride, and phosphorus chlorides must usually be handled in enamelled ware. This equipment is also used when it is necessary to nitrate directly with dilute nitric acid or when light-colored products are being purified by re-crystallization. It has gained favor with the manufacturers of food and dairy products, for, although there are metals and alloys which do not corrode under conditions existing in these industries, they occasionally give to these products undesirable metallic flavors. This is particularly true in the dairy industry.

Rubber has achieved recognition as a valuable structural material both in the hard and soft form. Hard rubber possesses excellent resistance to all concentrations of hydrochloric acid as well as equivalent concentrations of sulfuric acid. This material is, how-

ever, restricted to use at temperatures usually below 50° C. It is now made in the form of pumps, piping, pipe fittings, cocks, etc., and usually gives good service if it is restricted to those uses for which it is intended. One disadvantage which this material has, is the similarity in its appearance to iron. Repairmen have often mistaken it for iron and have seriously damaged it by applying a wrench before they discovered their mistake. The manufacturers have realized this difficulty but claim that they cannot give their goods a distinctive color without impairing its quality.

Hard rubber is used principally for storage, transportation and pumping of hydrochloric acid. It gives quite satisfactory service, too, with cold acetic acid of all concentrations. However, reports have been received that glacial acetic acid tends to alter the hard rubber and cause leakage at wearing surfaces. Nevertheless, a reciprocal pump used in this service for over three years seemed to show no ill effects.

Hard rubber fittings are of great value in installations where more than one metal is used in construction. If iron and copper or aluminum and copper lines have to be connected to the same equipment, hard rubber fittings effectually prevent electrolytic corrosion.

Benzol, chlorbenzol, phenol and similar products should not be allowed to come in contact with hard rubber equipment nor should nitric acid and the higher concentrations of sulfuric acid.

A new application of this material is its use as a lining in tanks and tank cars. The American Hard Rubber Co. have installed several of these linings during the past two years.

The principal use for raw rubber is to be found in the lining of wooden tanks for the storage of hydrochloric acid. The Goodrich Rubber Co. has usually made these installations because of special precautions which have to be taken. A tank lining of this type was installed for the Grasselli Chemical Co. in 1900 and at last reports was still in service. A recent examination showed that vulcanization had progressed only half way through the layer of raw rubber.

Lead Linings.—Occasionally it is necessary to resort to a lead lining in cast iron or steel equipment. Since there are very few processes, however, in which heat transfer is not an important factor, attention should be called to the sacrifice in efficiency that is involved in the use of such an installation. The low price of

lead always argues in its favor and one is often prone to neglect considering the cost of operation or cost of inefficiency involved in its use. The principal apparent cost is in its installation. It is practically impossible to overcome one objectionable feature of the ordinary lead lining, namely, the very thin layer of air between the lead lining and the container. This layer of air has been known to reduce the effective heat transfer of a steam-jacketed container at 100° C. to as low as 1 per cent of its normal efficiency without the lining. It is difficult to translate this loss of efficiency into dollars and cents, but nevertheless this factor is worthy of more than passing thought. The Zeitler construction, described in another part of this paper, seems to overcome the difficulty by assuring continuous metallic contact of the lining with the container wall.

Conclusion

The field covered in this paper is a very broad one and consequently only the more important subjects have been touched upon. Even some of these have had to be briefly treated. The limitations of iron and steel are fairly well known. Copper, tin, zinc and some of the precious metals have valuable applications as have also metallic protective coatings, wood, brick, cement, fusible alloys, paints and varnishes. Each of these subjects could furnish interesting material enough for a paper in itself. The value of such conclusions as have been given here is largely due to a standard method of determining the relative suitability of materials and, in case of metals and alloys, a standard method of corrosion. Certainly, we should all be grateful to the duPont Co. for their unselfishness in allowing their data to be published.

In conclusion, it may be timely to call attention to the fact that a high initial cost of equipment negatively accelerates the cupidity (and oftentimes good judgment) of the purchaser and for this reason, more than any other, we do not possess the abundant data and experience which might otherwise convince us of the greater ultimate economy of the more corrosion-resistant equipment.

The material which is selected for equipment may oftentimes determine whether a process will be a success or a failure and I believe that we may consider it to be a sign of progress on the part of chemical engineers that they are showing more interest in the suitability of materials of construction and thereby combining better methods with economic costs.

"Laboratory Corrosion Tests"—W. S. Calcott and J. C. Whetzel

Discussion

Dr. N. K. Chaney: In the case of the dry battery business we have a very specialized case of chemical corrosion—that is, the so-called local action of the electrolyte upon the zinc container. This has necessitated the development of very precise and elaborate methods for quantitatively determining the rates of this corrosion or "shelf action" under various conditions and with various materials. One of the greatest difficulties encountered in such laboratory methods is the evaluation of uneven corrosion or pitting. If the corrosion is fairly uniform, the weight loss is a satisfactory measure; but if the corrosion is local and uneven, its effects are much more serious than the weight losses indicate. I wonder whether there are suggestions as to the proper weighting of irregular corrosion losses in the investigations carried on by the authors of the present paper.

Dr. Jerome Alexander: The point just brought up by the last speaker prompts me also to ask this question: What effect upon the corrosion of metal may be traced to the preëxisting presence of a small amount of impurities in those metals? And, second, what effect has the heat treatment, especially the speed of chilling, which affects the surface of the metal? I don't know whether you have investigated these questions or not.

Mr. A. E. Marshall: Mr. Calcott made reference to the necessity of giving preliminary treatment to metals before recording corrosion tests. A short prior treatment is also necessary in the case of non-metals. For instance, in determining the corrosion of Pyrex, or any type of glass, it is necessary to follow this procedure, because you get a temporary initial solution rate of 300 to 400 per cent of "normal." It is also true in the case of fused silica. We made tests some few years ago, and found a higher initial solution rate, which disappeared at the end of a few hours. If the figures were taken for the initial rate, they would be entirely misleading and not at all true.

Mr. Emerson P. Poste: Mr. Chairman, the point just brought out has a very interesting parallel in the action of acids on enamels.

The Bureau of Standards found that certain enamels showed an initial loss of gloss on one-hour test with practically no greater action on 1,000 hours' test.

I should like to ask the author of this paper as to the method used by him to determine the resistance of enamels. The American Ceramic Society has a committee working on the determination of the acid resistance of enamels and we should greatly appreciate information on this point.

Dr. Charles F. Hollander: I should like to ask the author of this paper how he determines the thickness of the materials after grinding "out" the pitted part of the alloyed material? Do you make the surface plane?

Dr. W. S. Calcott: We use a rectangular specimen of definite dimensions, approximately the same size in all cases; a comparatively thin specimen, so that we can ignore edge pitting. We then reweigh the metal and calculate the equivalent thickness of the metal removed. Does that answer your question?

Dr. Hollander: Do you mean the average thickness of the specimen after grinding off the pitting?

Dr. Calcott: No; we do not actually measure the thickness of the specimen at all, but simply weigh it and determine its dimensions with the micrometer, and from these determine its area. Then if it is pitted, we grind it down until the pits disappear.

The development of pitting in the metal can not be ignored and this factor must be included in the results. To determine the magnitude of the effect, we grind down on a metallographic grinding set until all the pits have just disappeared and until solid metal is reached. The loss in weight during this grinding is determined, and we can then calculate the effect of the pitting.

Regarding the first point, we consider that a pit one-eighth of an inch deep is just as bad as if the metal had been all eaten away one-eighth of an inch, because the metal is no stronger than its weakest point. Therefore we grind out the pits to reduce its thickness to the depth of the deepest pit. If there is a pinhole in it, it is just as bad for use in manufacture as if the whole of it was gone.

On the question of impurities and heat treatment, we have not studied heat treatment. We found very remarkable effects due to the presence of small amounts of impurities. In one case the presence of 0.01 per cent hydrochloric acid in a certain solution pro-

foundly altered its action on an aluminum surface; without the hydrochloric acid it resisted well, but in its presence deteriorated rapidly. For this reason plant solutions of indefinite composition are frequently used in making our tests.

In regard to testing enamel, we have had occasion to do this very seldom, and simply obtained small enamel-lined cups and carried out the tests, except that we conducted the tests during a much longer duration of time, sometimes as long as a month instead of the ninety-six hours usual. This was done because we thought that in this case there might be considerable difference between the initial and steady rates of corrosion, due to a change in the character of the exposed surface.

Dr. Jerome Alexander: I think the suggestion of the speaker about the effect of impurities acting on the metal is very valuable. A few years ago there was a paper published in the Journal of the Society of Chemical Industry which reported that organic acids, when very dry, will attack metals seriously. Thus, very dry acetic and lactic acids attack aluminum. But the point that I want to get at is, what was the effect of small quantities of *impurities in the metal itself,* and not in the solution that acts on the metal. How do the impurities in the metals themselves affect its attack by the various solutions?

Dr. Calcott: We have not studied that particular point to any great extent in this particular investigation, but our experience in this particular case indicated that there was only two-tenths of a per cent of impurity in the aluminum with which we were dealing. Slight variation in the quantitative and qualitative characteristics fundamentally affect the aluminum.

Dr. Alexander: I wondered if things like that did not account for the effect on metals. Very slight traces of impurities may be present and the results, or some of them, may not be due to experimental errors as much as to the fundamental fact that impurities are responsible for those errors.

Dr. John C. Olsen: I want to ask Dr. Calcott with relation to the surface film which is removed after a short time—whether that surface film is chemically different from the rest of the metal, or is physically different or electro-chemically different, or whether he has any idea as to what that surface film is?

Dr. Calcott: We have very little idea. In some cases we have

found definitely that it was chemical. In the case of iron there is sometimes a small amount of iron oxide on the surface. In steel it is sometimes due to the working of the steel which has left surface layers which are electro-positive to the body of the steel. In the case I had in mind it was aluminum, which has a surface film of oxide, so we concluded that the surface film might be due to any one of these causes. But there is nearly always a surface film of different composition from the body of the material.

MR. P. H. GROGGINS: May I ask whether the corrosion during the first four hours might not be considered as the true corrosion rate, as the metal oftentimes forms a protective surface; also whether the corrosion has thus not been retarded by subjecting it to continued treatment, whereas in plant processes constant recharging and washing of apparatus eliminates this protective action?

DR. CHANEY: Some of the points raised by the preceding speakers have been covered by our own investigations on the corrosion of zinc. The same factors are present in all corrosion experiments, although their relative quantitative effects may vary widely with the alloy or metal and the conditions of test employed. For instance, as Dr. Alexander suggests, small amounts of certain impurities make large differences in corrosion. The impurities may sometimes produce their effects if in the electrolyte or corrosive solution as well as if in the metal itself.

But the most important point in developing any consistent type of corrosion test is the " preliminary treatment " of the test specimens so that a characteristic and reproducible physical surface is always presented by all test pieces undergoing direct comparison. The initial corrosion rates may be varied enormously by purely physical modifications of the surface.

It is possible so to work the surface of a metal as to cause an initial inhibition of corrosion as in pack-rolled and strip-rolled zinc. On the other hand, by sand blasting, buffing, etc., the initial rate may be unduly accelerated. In every case we have to distinguish between the initial rates (whether retarded or accelerated by the preliminary treatment) and the normal rate after corrosion has penetrated and removed the original surface film. This may be done as the authors of this paper suggest, or the surface may be artificially prepared by mechanical working, or by corrosion with acids before the regular test is commenced. For example, a simple way of removing a definite

quantity of metal from the surface without mechanical stresses being set up is to corrode the surface in a suitable acid until a definite quantity of gas (usually hydrogen) has been evolved.

In our practice the tests are continued for a sufficient time to carry the corrosion well over the initial period so that the weight losses represent the later corrosion rates to a predominating degree. Except where the nature of the corrosive medium and metal is such as to give rise to protective films, the rate of metal corrosion is usually a continually accelerating one, quite the reverse of that referred to by Mr. Marshall in the case of glasses and enamels.

PRESIDENT HOWARD: I should like to ask Mr. Calcott whether he has tried any experiments in passivifying metals? That is a subject which is increasing in importance. The Bureau of Explosives a short time ago accepted as standard practice for shipment of hydrofluoric acid metal drums which had been passivified by preliminary treatment with hydrofluoric acid. Drums, passivified in this way, are acceptable and their use is being extended—that is, steel packages in place of the old lead packages. There is another point to which I do not think there has been given much, if any, study, and that is the possibility of heat treatment to increase resistance to corrosion. Aluminum, for instance, is rapidly corroded in sea water. Heat-treated, the same aluminum is highly resistant to sea water. It seems to me that this indicates a very interesting field for experiment with other metals, to see whether other metals would not have their resistance to corrosion modified very greatly by heat treatment.

DR. POSTE: Bearing on that point, with specific reference to open-hearth steel, I have looked up several references and remember one which stated that under certain conditions overheated steel corroded 20 per cent faster than normal steel.

DR. OLSEN: The point has been brought up with reference to small impurities, and I should like to ask whether an analysis was made of the metals which are given in these tables, or whether the composition is known. I may have overlooked it, but I desire to ask whether the composition of the metals is given in the published report?

DR. CHANEY: By heating rolled zinc up to a point of rapid recrystallization and cooling, we have found that the corrosion rate in acids is reduced about one-third. Unfortunately, however, the desired mechanical properties are also destroyed, so that this has no practical significance to ordinary uses of sheet zinc.

MR. JAMES G. VAIL: I have been interested in the effect of silica in solution on some of these corrosion problems. Some of you may have seen an article by Dr. John C. Thresh, published in the Journal of the Society of Public Analysis (November and December, 1922), in which he shows that silica to the extent of one in two hundred thousand in a certain water supply would prevent the solution of lead in the pipes through which the water was delivered, and render safe an otherwise poisonous supply. Another case in which silicates are effective is to stop the corrosion of aluminum by sodium carbonate. (Seligman & Williams, Journal of Institute of Metals, *28, 297–8* (1922)). More lately there has been a piece of work done which shows that silica in hot-water supply systems added in the form of sodium silicate will prevent the continuance of corrosion already started. (C. R. Texter, American Waterworks Association, Spring Meeting, 1923.) In that case it is quite evident that there is a coating formed on the metal. In other cases it is not so evident. The effect of soluble silicates on corrosion is worthy of much more careful consideration.

MR. CHAS. WADSWORTH, *3d:* In connection with silica as affecting corrosion, there is a patent which came out rather recently on manganese and silicon in copper alloys, the resistance being attained by putting manganese and silicon in the alloy. In this case it is the silicon which seems to act as a preventive agent, but it is suggested that the surface film, which is the important thing, may be silica.

DR. ALEXANDER: I wonder if the gentleman has considered the work of G. Tammann, of Goettingen, regarding gold alloys? He found that corrosion begins at certain percentages where apparently the gold ceases to protect, by enclosure, the weaker metal. I do not now recall the details, but it seems to me those experiments have a direct bearing on the question in hand, the production of metal films.

MR. H. H. MEYERS: I should like to ask whether the rapid rate of corrosion occurs in intermittent use of metals, or whether the rate would be the normal one?

DR. EDWARD BARTOW: Have the authors considered the physical structure of these metals? They speak of corrosion decreasing as time elapses. It is known, of course, that surfaces of crystals will corrode more rapidly along certain axes than along others. When the metal is polished certain surfaces will be exposed, but after corrosion for a while, different sides of the crystals will be exposed, and

the corrosion will be less. If this has not been considered, I think it should be.

PRESIDENT HOWARD: Mr. Calcott, will you reply to these last points?

DR. CALCOTT: I think I should like first to make clear that our idea in this whole study was not to go into the theory of corrosion so much as to select from the different materials offered on the market from which we could build apparatus, those which would be most suitable. At the time the bulk of this work was done we had no opportunity to make a microscopic study of the samples or even an analysis in many cases, which is the reason for the omission of the analyses from the report.

DR. OLSEN: Have you some?

DR. CALCOTT: We have some, but not many. Take, for instance, steel. We took the mild steel that we got and tested that.

In regard to passivity, we have passivified metals several times, usually by adding some substance that we know would form a protective coating. We found on the question of the intermittent use of the apparatus that, judging by experience, the rate on the second 48 hours was the true rate. We found that by the use of the initial rate we arrived at a very low figure, not warranted by the actual life of the apparatus. If we take the steady rating, we will arrive at a figure much nearer the correct rate, unless there are extraneous facts entering in. For instance, in the case of a metal subjected to intermittent usage, and where we know that the oxide is to be acted on and the metal is not, our figures would be almost useless. Copper, for instance, oxidizes readily, and tests of that nature would be practically worthless.

The crystal structure we have not investigated, for the reason that I gave first, that our efforts were directed primarily toward selecting material which would give the most advantageous results. We had no time nor material with which to make microscopic examinations.

DR. ROBERT T. HASLAM: Dr. Calcott has recommended the second 48 hours, whereas Dr. Chaney uses the total time from the start of the corrosion test. I think the second 48 hours is preferable, because there may be either an increase or a decrease in corrosion during the first few hours. And if you take the rate of corrosion from zero time you are averaging two factors, initial corrosion and normal corrosion. So it seems to me that the second 48 hours should

give more comparable results than the rate of corrosion as determined over entire time.

MR. JOHN P. HUBBELL: There is a slightly different type of corrosion in which the surface film is extremely important. On metals which are used to resist atmospheric corrosion, particularly zinc, a protecting film is formed. In determining the probable life of such material it is not so important to know what that film is as to know what factors will form and remove it. We have been trying to work out a scheme to accelerate atmospheric corrosion. The problem has resolved itself into a study of those atmospheric conditions which favor the formation of protective coatings and those which favor the removal of the coatings. By properly alternating these conditions we hope to develop a test whose results will be comparable with atmospheric corrosion.

DR. HOLLANDER: I want to ask Mr. Calcott if he has not found that it makes a great difference how much of the reagent acts on the surface exposed? We constructed a piece of apparatus out of mild steel, and conducted a very long series of experiments in the laboratory, testing the material for thickness before and afterward, and found absolutely no corrosion which could be detected with the micrometer. We constructed later similar apparatus to that, but very much larger, although out of exactly the same soft steel with the same welds done by the same manufacturer, and so far as we could ascertain made entirely in the same fashion as the small apparatus. In the large apparatus we found, however, a corrosion which was prohibitive, and which we could only explain in this way—that there was in the large-size apparatus a larger volume of reagent on a comparatively smaller surface. Have you standardized the volume of solvent to be taken to the unit of surface?

DR. CALCOTT: The amount of the solvent must be sufficiently great so that the strength of the solution does not vary appreciably. For the larger rates of solution we would have to use a larger amount than with low rates of corrosion. We have had some experience, however, in finding that different metals were used in the stay bolts from the other portions of the apparatus.

DR. HOLLANDER: In these cases all joints were welded by the same manufacturer, and we had every reason to believe that it would act the same on the larger one as the smaller one.

MR. POSTE: Regarding the corrosion of welds, I have in mind a

specific case in which a steel tank was made by the oxy-acetylene process, using a filler of a composition essentially that of the plate. After a short period of use the filled-in metal was eaten out in a manner suggesting cutting out with a chipping hammer. In melting the filler into place the carbon is greatly reduced. There are also structural differences between filled-in and base metal. In general the conditions are such as to render the filled-in metal electro-positive to the original plate. It therefore suffers under corrosive action, as compared with the plate.

Mr. Robert J. McKay: The larger volume of corroding agent in practice, as opposed to the smaller volume in laboratory test, affects the rate of corrosion seriously, because the larger volume is capable of carrying more dissolved oxygen. The importance of the dissolved oxygen factor has perhaps not been sufficiently emphasized in this admirable paper. Except where the corroding solution contains a strong oxidizing agent, the attack is much more rapid when oxygen (or air) is present, owing to its depolarizing effect and its ability to react directly in corrosion. The volume of solution is important because oxygen is sparingly and slowly soluble. It is rapidly exhausted during corrosion and the furnishing of a constant fresh supply of air-saturated corroding solution is sure to produce maximum corrosion.

President Howard: Regarding the question of welding, that is a most important matter in steel apparatus. A good many years ago I built some steel tanks for making oleum, using acetylene welding. The tanks failed in three days, in the welds. The same tanks were then made by a Wilmington firm, the Pusey & Jones Company, by the old-fashioned welding process, which has been used for many years in making the furnaces for Scotch boilers. I understand the process consists of bringing the metal up to the welding heat by producer gas or water gas, or something of that sort, with powerful blasts on both sides, and then the joint is rolled together, and it is essentially a hammer weld. Those same tanks were put in use with exactly the same thickness in 1907, and are still absolutely intact and operating today, in the production of oleum. There was just the difference between the types of weld. The steel plate in both cases was intact. Acetylene welding is a very dangerous thing to use where there is an acid on one side and water on the other side of the joint.

This particular tank, I may say, was water-jacketed. A slight

porosity of the weld, if you have only acid on the inside, would do no harm. But in this case the slight porosity allowed the mixture of water with the oleum, the temperature was up around 140 degrees Fahrenheit and that started rapid corrosion where the acid was weak, and it went straight through.

Acetylene welding for steel pipes holding corrosive gases, like dry sulphur dioxide, will last indefinitely; but if those same joints were put under water, they might fail very quickly. The electric resistance weld seems to stand very well, about the same as the old hammer weld. But the electric arc weld is porous and should be used with a great deal of caution.

Tests made of acetylene welds are of little value because it is entirely possible to make a weld in this manner that is not porous, but it is apparently very difficult in doing large work commercially to avoid some spots that are porous. For instance, before building the tanks just referred to, small test tanks were made by acetylene welding, filled with oleum and immersed in hot water for three months. At the end of that time there was no corrosion visible and on the strength of this test the large tanks were ordered, which failed in three days.

DR. HOLLANDER: We realized that, and in many cases we specified that no calking should be done whatever. Any slight porosity found by having a pressure of air on the inside of the apparatus of fifteen or twenty pounds could be discovered by putting soap-suds solution on the outside. That shows the porosity very quickly, much better than the ordinary hydraulic test will, which does not show anything, even if you let it stand a long time.

MR. W. H. LEVERETT: In one of our plants, in a reclaiming operation, welding was called for under circumstances which indicated either acetylene or electric welding. Anticipating the danger of corrosion due to electrolysis, an attempt was made to adjust the composition of the bar used for welding, so that the resulting weld would be of the same composition as the original metal. The only result was to make the weld electro-negative with respect to the balance of the apparatus, and the sheets directly on each side of the weld were corroded through in a week, while the weld stood up like a rib.

PRESIDENT HOWARD: Is there further discussion? Dr. Calcott, do you want to make any further statement?

DR. CALCOTT: I have none to make except in reply to Mr. Mc-

Kay's point. The supply of oxygen to the metal under attack is a very important consideration, and is the reason we use, in testing, the actual solution employed on a large scale. I think the point is a good one, and should be borne in mind in all tests.

PRESIDENT HOWARD: I declare this discussion closed and we will go to the next paper.

MR. W. R. CLYMER (communicated): The matter of corrosion, being very complicated, much study is needed in any particular case to determine both the causes and the remedy. Oxy-acetylene welding is not the simple matter it is sometimes thought to be, and problems arise in connection with it that also need careful and properly directed research for their solution. It should also be remembered that in 1907 welding was in its earliest stages, and that great advances have been made since that time in both its theory and its practice.

The experience of President Howard would seem to have been with welds that were not properly made, because he speaks of the porosity of the weld. A properly made acetylene weld is absolutely impervious to the passage of any liquid or gas, and thousands of them are in use under heavy pressure of many kinds of liquids, with entire satisfaction. Dr. Poste has referred to a tank in which the filler used was as nearly as possible of the same composition as the plate. If the welding rod was originally of the same composition as the plate, it would not be so in the weld, and if, in order to allow for the alteration due to the welding, the rod were made of such a composition as would actually result in the weld being the same chemically as the plate, the chances are much in favor of bad welding. Dr. Hollander says that he has specified in many cases that no calking shall be done, and that air pressure and soap-suds were used to test the porosity. As stated before, a properly made acetylene weld will meet this test properly, and, as a matter of fact, this test is used every day in many welding shops, and has proven its value for the purpose.

Dr. Poste has stated that as a general proposition the weld is electro-positive to the plate, and Mr. Leverett found that under certain conditions the weld was electro-negative with regard to the balance of the apparatus. It would therefore seem possible, although it might be difficult, to make a weld which would be neither electro-positive nor electro-negative to the plate.

Welding is not a matter of simply melting metal, but is just as much a matter of application of scientific principles as any other

process involving metallurgical or chemical reaction, as has been shown by experience as well as theoretically. In many special cases, welding has been investigated along such lines and problems have been solved and practical results obtained, which have been commercialized with satisfactory results.

It might be remarked that a number of corrosion problems in chemical apparatus have been studied, and that, as the difficulties encountered have been entirely overcome in these cases, it does not seem unreasonable to expect that in other cases equally satisfactory results should be obtained, provided that the problems are attacked by those who are thoroughly familiar with the possibilities of welding and with the methods used in scientific research.

"Materials of Construction for Chemical Apparatus"—Harold F. Whittaker

Discussion

Mr. Whittaker (before presenting paper): There are two typographical corrections which I wish to make. The first, which you will find on page 22 of Mr. Calcott's paper, pertains to the formula on the middle of the page. The "2.54" should be cubed instead of squared. The final term is correct as given. And then, on the cover of the preprint of my paper, my address should have been given as "Washington, D. C.," instead of Minneapolis. My name was evidently confused with that of another man in Minneapolis.

The paper is much too long to read here, but I should like to say that the object in collecting these data was to amplify and correlate the experimental data obtained at the Jackson Laboratory of the duPont Co., and to present it in such form that valuable conclusions could be drawn from it. The essential features of the original report are embodied in this paper, and, although no claims are made regarding its completeness, it is believed that not only will interest be stimulated in this subject, but also the mental attitude of engineers in the selection of the proper structural materials may be changed somewhat. Ultimate cost of chemical equipment is an important factor to be considered before final selection is made, and it is hoped that the data presented in this paper will influence engineers to believe that the cheapest is not always the least costly.

Mr. A. E. Marshall: There are several points in Mr. Whit-

taker's paper that I should like to discuss for a moment. For example, reference is made to materials suitable for distillation of acetic acid, but no reference is made to silver. In European practice it is customary to make use of silver, and I saw a plant in 1919, built in 1904, which had run continuously for fifteen years, with the original silver coils and slate tanks for the storage of all strengths of acetic acid. The silver coils were quite thin, about one-sixteenth of an inch thickness, and they showed no deterioration in fifteen years.

Reference is also made to "a special grade of Tantiron which is claimed to be resistant to hydrochloric acid." I should like to say that from the result of our experience we are satisfied that the special grade of Tantiron is not resistant to hydrochloric acid; in fact, it is not so good as some of the other alloys.

In the case of enameled equipment a suggestion is made that it might be desirable to use a nickel steel as the metallic support for the enamel, and reference is made to the so-called Platinite alloys. While Platinite alloy has the same coefficient of expansion as glass at around 200° C., there is a considerable difference at the temperature at which the enamel would flow, so the enamel would crack off on cooling and it would be impossible to get a sound article. I am familiar with this fact because of experiments made in reinforcing glass with Platinite and other alloys. In the case of monel metal we had occasion last year to make use of this alloy in a pump designed for handling 4 per cent sulphuric acid containing impurities. The pump as originally built utilized antimonial lead parts, and in this form it failed in less than three weeks. The parts which failed were replaced with monel and the pump put back into operation. The pump has been in service about eleven months, handling the same solution, and when it was torn down about four months ago was found to be in good condition.

Mr. Poste: Inasmuch as Mr. Whittaker has referred to enameled equipment especially, I should like to make a few remarks about the paper, and in doing so I will endeavor to present the point of view of the enameling industry as a whole.

Specific reference to certain statements in the paper under discussion may serve to point out useful facts in connection with the use of enameled equipment.

In speaking of antimony chlorides as chlorinating agents, the author states that "these reagents are very corrosive and have been known to attack enameled equipment in a short time." I am not sure

as to the exact case that may have been in mind, but I do know that some equipment that has been used for this type of work has failed as a direct result of imperfections in the steel on which the enamel had been fused. The shapes were pressed containers made from inferior stock, the slag inclusions in which had been drawn out in the pressing operation and had later reacted with the enamel causing weakness therein. The point in mind is the fact that the enameler has often had difficulty in getting stock of the desired quality for certain lines of product, and in such cases field trouble has often been taken as indicating an inherent chemical weakness of the enamel as a whole when such was not the case.

A further point with reference to imperfections in base metal and defects in enamel is involved in cast-iron apparatus. A certain type of field failure originally considered as a weakness of the enamel was found to be due to porosity of casting which allowed the steam pressure in the jacket to become effective under the enamel and force it off. After considerable research an iron was produced that would not develop this porosity during the enameling operation and this type of trouble seems to be at an end.

The author suggested a certain alloy as more desirable for a base metal because of a coefficient of expansion close to that of enamel. But Mr. Marshall has suggested that such alloys are not regular in their coefficients of expansion through the range involved in the cooling of enamel. This seems to be a very important point. That the relation between the coefficient of expansion of the metal and enamel is important is recognized by the enamel technologist. But he does not think that they should be equal. Enamel is strong in compression and weak in tension. It should, therefore, be kept under compression. To that end the coefficient of expansion should be lower than that of the base metal. Too big a difference will result in difficulties, however. Further, the contraction of enamel and metal should be of the same general order throughout the range of temperatures involved in cooling from the molten condition of the enamel. In this regard the alloys suggested would seem to be wanting. I should like to ask if any actual attempt to enamel such alloys has been made or was the suggestion on a purely theoretical basis?

With further reference to the matter of coefficient of expansion, we have inherited from European investigators a set of factors to be used in computing coefficients of expansion from percentage com-

position. The Bureau of Standards has investigated this matter and found that some of these factors are incorrect. If interested in this general investigation, one will find the work reported in the Journal of the American Ceramic Society, Vol. IV, page 628.

In general, the relation of the base metal to the enamel is an important one and involves the metallurgy of the metal in its original fabrication and under the heat of the enameling furnace.

In certain cases the author has stated that nitric acid has seriously attacked enamel. I think that each of the several manufacturers puts out several different formulas, each suited to a particular type of work. In some cases mistakes have been made in testing or using relatively soft enamels under severe chemical conditions for which they were not intended. Obviously an enamel designed for the dairy industry might fail with a mineral acid. Such cases are on record and have often led to an unwarranted prejudice against the enamel. On the other hand, there are on the market enamels commercially resistant to nitric acid, as suggested in Table X of Laboratory Corrosion Tests by Calcott and Whetzel.

The manufacturers of enameled equipment are quite familiar with their product in terms of its fitness for various types of work and are very anxious that it be used under conditions of satisfactory service. The prospective user protects himself and the manufacturer alike when he accurately states the essential mechanical and chemical conditions when making an inquiry.

It is stated that no "method of applying the enamel coating will allow it to withstand the shock of a dropped monkey-wrench or other tool." It seems to the manufacturer entirely unreasonable that the user should expect enamel to withstand such carelessness as that referred to. An immense amount of enameled equipment is used in industries employing a cheaper class of labor than that usually found in a chemical plant, but cases of damage from this type of carelessness are very few.

In connection with definite chemical operations, Mr. Whittaker has suggested enameled equipment in a dozen or more cases. And he has failed to mention it in several other instances in which it has given satisfactory service. He has pointed out its various disadvantages, some of which have been covered above. He has stated that its chief use is in connection with the food industries; that in chemical operations it is only used when nothing else will do, and that "the shortcomings of this type of equipment outweigh its advantages."

The manufacturer is aware of the difficulties which have been experienced in various instances. Some of these have been incidental to the development of a new industry. Others have resulted from a lack of understanding on the part of the manufacturer of the properties of his product and the use to which it was to be put. Some have been due to a lack of proper understanding and care on the part of the user. But marked progress has been made in the methods of manufacture, and efforts for further improvement are constant; the maker knows more as to the possibilities and limitations of his product; and the user more fully appreciates the necessity for proper selection and use of the apparatus.

In view of these facts, it is evident that the advantages of this type of equipment far outweigh its shortcomings.

MR. WHITTAKER: In reply to Mr. Marshall's remark I should say that silver was overlooked. We do not claim that each one of the lists in the paper is complete, but that they indicate our own experience. In some cases references have been made to more pertinent information to be obtained through the literature. Although we knew silver was not affected by acetic acid, it was left out due to oversight, and I agree that it should be included. It would probably be better to use silver than aluminum, but at the time this paper was drawn up somewhat different economic conditions prevailed; industry was returning to a peace-time basis and, due to strict economy, the use of silver was not given much thought.

Referring to the point that he and Dr. Poste made about the base metal, the references were obtained from the work by C. E. Guillaume, Comptes Rendus, 170, 1433 (1920); 170, 1555 (1920); 171, 1039 (1920). The work was begun about 1898, and I believe interest is still active in this work. Mr. Baker and I drew up a number of curves that I think showed the coefficient of expansion of nickel steel alloys up as high as about 400 degrees Centigrade, or about 750 degrees Fahrenheit, but no data were available for such high temperatures as Dr. Poste mentioned. No direct comparison was possible therefore.

A platinite composition which would, of course, contain traces of silicon, manganese, etc., could be devised that would have a greater or lesser coefficient of expansion than the glass enamel coating. Conclusions were drawn that the proximity of these coefficients would obviate the checking and destruction of enamel equipment under the

conditions of *actual service*. Owing to lack of facilities for doing this type of work, no actual tests could be made.

Mr. Poste mentioned corrosion of enamel. I have seen an example of this in a vessel in which antimony chloride had been used. The enamel had been eaten away in very much the same manner that a cutworm works in a garden. It was eaten through in spots around the sides of the vessel slightly above and below the liquid level and looked as if a cutworm had been swimming around on the surface of the liquid, and had been chewing off the enamel on a line about three-quarters of an inch wide all around the surface of the machine. There are cases where enamel chips off due to other causes. In the majority of these cases, however, I think the failures are due to expansion of the base metal and the formation of small cracks in the enamel coating. These cracks are due to pressure expansion or temperature expansion or differentials between the enamel and the base metal, or possibly to the fact that the enamel is not in close contact with the base metal due to a spot of sand or oxide. There are some instances, however, where enameled equipment has failed due to corrosion of the enamel itself.

We can not rely on enamelware especially designed for chemical work not to fail. The manufacture of enamelware which is designed for chemical use is a much more difficult problem than the manufacture of enamelware for dairy purposes, of which many thousand pieces can be made each day. Chemical apparatus is usually large and bulky, and is generally considered to be a special production problem. It is not strange, therefore, that enamelware manufacturers should be more interested in the simpler and more profitable production problems.

Oftentimes during shipment a heavy shock will affect enameled steel, so that there are points at which cracks occur which are absolutely invisible. When subjected to service conditions, however, it is only a short time before the enamel chips off.

Mr. Poste: Mr. Whittaker has just stated that "oftentimes during shipment a heavy shock will affect enameled steel, so that there are points at which cracks occur, which are absolutely invisible. When subjected to service conditions, however, it is only a short time before the enamel chips off."

I feel that the word "shock" hardly applies. If, during transportation or use, mechanical strains are produced in the steel so as to

deflect the metal seriously, the enamel will become fractured. But it would take more than a "shock" to do this. Steel structures to be enameled are designed with at least twice the factor of safety that would be used in the absence of enamel to assure rigidity under normal conditions.

It has also been stated that "chemical apparatus when enameled is . . . generally special. . . ." It is true that a given assembly of equipment may be special, but the elements entering into it are generally quite standard, particularly when cast-iron equipment is involved. Obviously the meeting of needs which the user thinks of as special, but with units which, to the manufacturer, are standard, is a very desirable situation.

MR. ARTHUR L. GARDNER: I would like to ask about this point. I had occasion to use enameled tubes, enameled on the outside, for the purpose of evaporating corrosive liquor, and the enamel failed always along the bottom of the tube. There was no corrosion of the enamel except along the bottom. We attributed it to thermal conditions there, but never obtained a satisfactory solution.

DR. POSTE: Were the tubes to which you refer U-tubes, "hairpins," as we call them?

MR. GARDNER: No; they were straight tubes about 4½ inches in diameter and 6 feet long.

MR. POSTE: It is very difficult successfully to enamel tubing and such work for the chemical trade is undertaken only in very special cases. If there is a seam in the stock due to welding or original imperfections drawn out lengthwise of the tube in its formation, there is liable to be a corresponding defect in the enamel. As a whole the enameling of a tube outside or inside is not desirable. Shorter pieces to be used as fittings can be fairly well processed on the inside. Long lengths are much more troublesome. Possibly these suggestions may have a bearing on the trouble referred to.

MR. R. L. HOLLIDAY: I should like to take exception to the statement made about silver for acetic acid. In Philadelphia there is a silver coil not five years old which has completely failed.

MR. E. L. WILSON: I notice that Mr. Whittaker mentions illium in his paper. We are now using illium in phosphoric acid manufacture and find that in spite of its high initial cost it can be used economically for small parts, such as valve seats, pump impellors, etc.

MR. P. H. GROGGIN: I should like to sustain Mr. Marshall in what

he states regarding the resistance of silver to acetic acid. Silver-lined coils are being used successfully on a large scale in this country in the manufacture of acetanilid and it has been found to be practically the only metal that stands up very successfully. Experience has shown that traces of hydrochloric acid will rapidly destroy equipment designed for glacial acetic acid, and, vice-versa, traces of acetic acid will often destroy equipment designed for the use of hydrochloric acid—witness the destruction of lead coils in an aniline reduction plant when a by-product hydrochloric acid contaminated with acetic acid was used in the reducer.

PRESIDENT HOWARD: I should like to suggest to the other gentleman who has had trouble with silver coils that he should investigate the purity of the silver used. It is quite possible that the silver was not pure.

MR. HOLLIDAY: It was bought for pure silver.

PRESIDENT HOWARD: It would be advisable to investigate it.

MR. MARSHALL: I do know of a case of failure in which the manufacturer of acetic acid had forgotten to make tests for the possible presence of hydrochloric acid, the trouble with the silver being really due to hydrochloric acid coming from the materials used in the original distillation.

PRESIDENT HOWARD: If there is no further discussion we will close this and proceed to the next paper.

The next paper on the program is "The Literature of Chemical Corrosion," by A. E. Marshall.

MR. A. E. MARSHALL (The Literature of Chemical Corrosion): The decision of the Council of the Institute to issue in monograph form the papers read by preceding speakers on various phases of chemical corrosion is considered as contributory evidence to the need for a more extensive literature on corrosion so far as it affects chemical engineering work.

The last decade has witnessed the recognition of chemical engineering as a distinct profession, and a comparison of the curricula of universities and colleges for the years 1912 and 1923 will provide evidence of the present importance placed on the training and industrial value of chemical engineers. Chemical engineering, while it extends into the fields of chemistry and engineering, does not conflict with the work of the chemist or the engineer. It has specific requirements of knowledge which are not essential factors in chemistry or

engineering, one of the most important being a familiarity with chemical corrosion and its effect on materials used in plant construction.

Corrosion resistance from the chemical engineering standpoint is distinct from the requirements for other branches of engineering work, even though the instrumental causes and effects are often similar. A survey of the available literature indicates a decided lack of reliable data, and the growing importance of chemical engineering demands the formulation of some definite plan and sequence of work, which will fill the gaps and permit the compilation of comprehensive and reliable data.

The hand-books of other engineering professions provide information on practically all the problems encountered in the practice of these professions. The mechanical engineer has his Kent, the civil engineer his Trautwine, and the electrical engineer his Foster or Fowle. The chemical engineer does not lack textbooks, but his textbooks are silent on the resistance of plant construction materials to the corrosive action of the raw materials and finished products of the chemical industry. The compilers of the textbooks are not to blame for the deficiency, as they have had no reliable sources to draw from, and the preparation of accurate data on such an extensive subject is too great a task for any one man to undertake.

One of the reasons which has been advanced for the present deficiency in chemical corrosion literature is the disinclination of manufacturers to publish results which might prove useful to competitors. The reading, at this meeting, of a series of papers based on work done in the laboratories of one of the large chemical manufacturing companies is an indication of a broadened spirit in the industry and is in conflict with the expression in Griffith's "Chemical Engineering Design" that "much of the secrecy connected with the prosecution of chemical manufacture relates to matters of chemical engineering alone."

Several of the laboratories attached to educational institutions have contributed excellent material on chemical corrosion and have laid plans for a further extension of this work. The importance of the subject would seem to justify an attempt to interest other institutions which possess the necessary directional and research facilities, in laboratory corrosion determinations, and to formulate some definite plan which would prevent too great an overlapping of effort.

A study of available corrosion data will disclose wide differences

in methods and in the expression of results, so while the figures in one paper will be comparable with each other, they will not be comparable with the results obtained by another worker.

The variants which can enter into laboratory corrosion determinations are so pronounced that comparative results can only be secured by the adoption of a standard method. To illustrate this point, a survey has been made of the methods used by nine investigators who have published corrosion data. No two were in agreement on all points of technique; in fact, there was evidence of widely divergent practice.

Dividing the determinations into stages, variations were found in:

1. Methods of preparing surfaces of material.
2. Methods of suspension in corroding liquid.
3. Degree of submergence.
4. Material at rest or in motion.
5. Corroding liquid at rest or in motion.
6. Constant strength corroding liquid or a fixed initial strength decreasing as the action progressed.
7. Methods of preparing corroded samples before weighing.

The same differences existed in the methods of expressing results, some of the figures used being:

1. Loss expressed as a percentage of original weight.
2. Loss in weight per unit area of exposed surface.
3. Loss in thickness per unit area of exposed surface.

The above summary will indicate the need for standardized methods, not only of performing corrosion tests, but also of expressing the final results.

Corrosion data based on laboratory results are valuable, but there is also a very definite need for performance records based on actual plant experiences over reasonably long periods of time. The provision of a useful literature of chemical corrosion, therefore, depends on research laboratory records and plant performance reports under usual and unusual manufacturing conditions.

So far, the needs of the chemical engineer for reliable corrosion data have been stressed, and a suggestion made as to the desirability of interesting research graduates in corrosion work. It has also been shown that wide differences in methods and expressions of results exist, and that there is a need for plant performance data.

There are several agencies already active in the collection of gen-

eral corrosion data, including the National Research Council, the American Society of Testing Materials, and the Prime Movers Association.

None of these bodies are undertaking the compilation of data designed primarily for the use of chemical engineers, and there is, of course, no reason why they should do so. It is recognized, on the other hand, that records of general corrosion work, as, for instance, corrosion through mine waters, hydrolized chlorides in boiler waters, etc., will have a bearing on certain phases of chemical corrosion, and that results of many strictly chemical problems will be of value to workers in the general field. Thus there is every reason why efforts made toward the establishment of authentic chemical corrosion records should be carried on with full recognition of the value of coöperation with other agencies now investigating general corrosion problems, without it acting as a deterrent to the establishment of a "clearing house" for chemical corrosion data.

The Constitution of the Institute of Chemical Engineers contains a clause which states that one of the objects of the organization shall be: "To publish and distribute such papers as shall add to classified knowledge in chemical engineering and shall increase industrial activity."

In the author's opinion the Institute could undertake no more valuable work than has been outlined in this paper, and suggests a committee be formed, to be known as the Chemical Corrosion Committee, and that this committee be charged with the duties of:

Coördinating and standardizing methods for chemical corrosion tests.

Collecting and checking available data based on laboratory tests and plant performances.

Developing a systematic scheme of research on the corrosion of chemical plant materials.

Interesting research workers in corrosion problems, and when desired assigning research studies.

It is his further thought that through the work of this committee the Institute would sponsor the publication of a series of monographs on "Chemical Corrosion."

MR. WHITTAKER: I think the Chairman of our Corrosion Committee of the National Research Council, Mr. Corse, is here, and he may have something to say regarding the correlation of information.

A MEMBER: Mr. Corse has just stepped out. Dr. Lathrop is here, of the American Society for Testing of Materials.

DR. ELBERT C. LATHROP: I want to take this opportunity to bring to your attention the work done by the committee of the American Society of Testing Materials, known as B–3. This work was undertaken last year and the first step was to draw up a very elaborate questionnaire which was sent out to some 250 men, and companies, known to be interested in the question of corrosion, both from the standpoint of atmospheric and chemical corrosion. Only a relatively small number of complete replies were received, but these will probably be drawn up in the form of monograph at a later date to be presented in the transactions of that Society.

Committee B–3 is very anxious to obtain the coöperation of the chemical engineers, because the chemical engineers will eventually say what non-ferrous metal will be used in the construction of apparatus. The aim of the committee is not to undertake research work on corrosion, but to try and work out satisfactory definitions for the terms used and to try to draw specifications for testing of a few of the best known kinds of corrosion. These tests will then probably be submitted to the various companies and individuals, and an effort made to determine how well various workers in the different laboratories can duplicate results on the same metal under standardized conditions.

PRESIDENT HOWARD: What is your idea, Dr. Lathrop, regarding the appointment of such a committee as Mr. Marshall has suggested?

DR. LATHROP: I think Mr. Corse is in a better position to answer that, because he is correlating the work on corrosion with other engineering societies. I know that this work is being carried on under a variety of topics, and in considering what Committee B–3 would take up we went over with Mr. Corse what other societies are doing, and we are confining our efforts to a single phase of the question. If Mr. Corse comes in I think it will be well to have him talk to us.

MR. MARSHALL: Prior to the arrival of Mr. Corse I should like to lay emphasis on one fact, and that is that the American Institute of Chemical Engineers should at some time or other decide to do something for itself, and not work solely through other institutions. It is quite true that the National Research Council can collect much valuable material on corrosion, but I do not think the facilities of the National Research Council can compare with the facilities of this

Institute in the matter of collecting definite information on corrosion, particularly the plant phases of it as obtained in actual works' practice. I should like to see a monograph on chemical corrosion go out from this Institute, carrying the Institute's endorsement, as a first effort toward meeting the needs of our own profession.

PRESIDENT HOWARD: Mr. Marshall, there is no motion before the meeting. Perhaps you will put your recommendation in the form of a motion, and then it can be discussed.

MR. MARSHALL: I would move that a committee be formed, to be known as the Chemical Corrosion Committee, and that this committee be charged with the duties of:

Coördinating and standardizing methods for chemical corrosion tests.

Collecting and checking available data based on laboratory tests and plant performances.

Developing a systematic scheme of research on the corrosion of chemical plant materials.

Interesting research workers in corrosion problems, and when desired assiging research studies.

PRESIDENT HOWARD: We should like to hear from Mr. Corse, and get his opinion as to whether there will be any duplicating of effort between such a committee and the National Research Council.

MR. WILLIAM M. CORSE: Mr. President, I just came in and did not hear the entire remarks of Mr. Marshall, but I am quite sure that any work which we contemplate at the National Research Council will not in any way interfere with the scheme which Mr. Marshall has outlined. The sole purpose of the Corrosion Committee of the National Research Council is to do what is being done here this morning, to stimulate interest in the subject and get committees to work on it. In other words, our Committee on Corrosion at the Council is a steering committee only, and has no intention of taking work away from technical societies such as this. If we can interest technical societies in this subject, to do what Mr. Marshall's motion suggests, it would be exactly what we would like to see done. I understood that the suggestion was made that a committee from this Institute consider the determination of a practical test for corrosion. I am not sure whether that matter was touched on by Dr. Lathrop, but I might say that our committee of the Council asked the American Society for Testing Materials to organize a committee on corrosion

of non-ferrous metals and alloys, about a year ago. They already had a Committee on Corrosion of Iron and Steel, known as A–5. The new committee which we suggested they organize is known as B–3, and Dr. Lathrop of this Institute is chairman of the committee.

The particular thing which we asked that committee to do was to determine a standard test for corrosion. If the members of the corrosion committee of this Institute are willing to help in this work, I am sure Dr. Lathrop's committee would be glad to coöperate. I suggest that the committee from this Institute coöperate fully with the committee from the American Society for Testing Materials.

To repeat what I said before, the National Research Council committee aims to interest people in this subject and to bring about the appointment of committees just as has been suggested by Mr. Marshall, so if we can act as a coördinating body, avoiding duplication, we have done what we planned to do. I hope that answers your question, Mr. President.

Dr. Jerome Alexander: In rising to support Mr. Marshall's motion, I want to point out that the problem which this touches is a highly specialized one, dealing with chemical corrosion. Professor Jackson has just told me that there is a committee from the United Engineering Societies dealing with corrosion in general, but that the committee is dealing with corrosion by the elements, ordinary meteorological elements, while the committee Mr. Marshall proposes is to study high specialized work. I take it for granted that any committee appointed under Mr. Marshall's motion would naturally get in with any other committees.

Dr. Reese: I am very much in favor of Mr. Marshall's motion and see no reason why we might not coöperate. I should think it very desirable to put the chairman of the committee from this association on the committee of the National Research Council if that is possible.

Mr. Corse: I think it is possible.

Dr. Reese: It would be desirable to have a member on each of these committees, who would either be members or would be directed to attend the meetings of the Council, and other organizations in this matter.

Mr. Corse: If the Secretary will send me a letter suggesting that the chairman of this proposed committee be added to the Research Council committee, I shall be glad to take the necessary steps to have that done.

Dr. Lathrop: The Committee on Testing Materials is largely made up of members of this Institute.

(Thereupon the question was put, and the motion presented by Mr. Marshall was adopted without dissent.)

Mr. Paul D. Merica (communicated): I am very glad that the Institute is devoting some of its time to consideration of this problem of corrosion, as evidence of the increasing realization by its members of its significance in connection with chemical manufacturing. As Messrs. Calcott and Whetzel remark, the success or failure of a process may often depend on the proper selection of the equipment materials.

Once this fundamental fact is realized the importance of developing precision methods of measuring corrosion resistance becomes at once apparent, and our appreciation is due the authors for the constructive work they have done in making critical studies of such methods and finally applying them to a variety of chemicals and materials commonly in use.

I fully believe that the authors have demonstrated that if properly executed, with control of known factors, a corrosion test, at least of the complete immersion type, may yield precise results possible of duplication at any time. There may still, however, be some disposition to doubt whether much of practical value may be inferred from such tests in view of the experience which most of us have had in predicting service behavior from laboratory tests. I think we should remember, however, that the art of mechanical testing of materials once went through almost the same course which corrosion-resistance testing is now taking. At one time, and not more than forty years ago, tensile tests made in one laboratory would not check those made in others, and it was not until the practice of such testing had been standardized, partly by private experiment and partly through the instrumentality of technical societies such as the Society for Testing Materials, that agreement was reached.

Furthermore, no one would deny today the value of the usual mechanical tests of materials, yet our course of inference from their results to the service behavior of the materials is still not entirely clear and depends on practical experience. And thus will it be with corrosion-resistance testing; our first task ended—that of the development of precise and duplicable methods of testing—the next and greater one will be to learn how to apply the results in practice. I

am thoroughly convinced that within a few years our effective knowledge of corrosion will be revolutionized, and certainly the authors have done much to show us the way.

Dr. Lathrop has described the purpose and work of a new committee of The American Society for Testing Materials: B–3 on the Corrosion of Non-ferrous Metals. It was my fortune to be chairman of a subcommittee of that committee, charged with making a survey of the practice and ideas of those in this country doing corrosion work on such materials. It was very encouraging to note the active interest in the subject and to realize how rapidly progress is being made by individuals in all industries in the practice of corrosion testing.

Dr. G. W. Thompson (communicated): I have been reading over very carefully the papers entitled "Materials of Construction for Chemical Apparatus," by Harold F. Whittaker, and "Laboratory Corrosion Tests," by W. S. Calcott and J. C. Whetzel. I believe that they contain some of the very best material which has been contributed to assist the work of the chemical engineer. I have concluded that it would be unwise for me to discuss either of these papers in detail. They represent an amount of work and research that is monumental in character. There are two thoughts, however, that present themselves to my mind:

1. As many of the materials used in chemical manufacturing apparatus differ in purity or composition, it would be exceedingly desirable if work could be done, preferably in a coöperative way, to determine the effect of these impurities upon the suitability of the materials for the particular uses they are to be put to. For instance, the presence of a small amount of copper in sheet lead used for acid chambers is generally considered desirable. There are differences of opinion upon this subject, both as to the desirability of copper and as to the quantity of copper that gives the best results. More information on this subject is desired.

2. Might it not be desirable for the Institute to have a standing committee on materials to be used in chemical manufacturing apparatus, which committee would be a kind of clearing house for data and also help in the development of coöperative work?

Mr. Percy C. Kingsbury (communicated): This paper is a very useful addition to the literature of corrosion. A great deal of what has already been published on this subject consists of data compiled

from laboratory work that does not parallel the conditions met with in the plant and which therefore is of little value to the plant operative.

The advantage of this paper is that we are told definitely what materials can be used to meet any specific corrosion problem and are not left to draw our own conclusions from the mass of curves and tables.

The author has, as he states, attempted to cover a very wide range, and in doing so has not considered such important factors in the selection of the material for chemical apparatus as comparative price and the practicability of working up the material into the shapes and sizes desired.

Furthermore, the various materials are mentioned without reference to their relative importance. In most problems relating to the manufacture or handling of corrosive materials to which the common metals are not applicable the first thought of the plant superintendent is chemicalware and the ferro-silicon alloys. Most of the acids referred to by the author are, as a rule, manufactured on the industrial scale in chemicalware apparatus, which is, however, mentioned only casually in this paper. Perhaps the author assumes that the use for chemicalware for such purposes is self-evident. Some of the materials referred to under " special metals and equipment " which are not much more than interesting curiosities of very limited application in the plant are given more prominence than the materials commonly employed in industrial work.

This is not intended to be a criticism of the paper, as there is naturally more to be said about a comparatively new material than about those with which everybody is familiar. However, it will undoubtedly be used for reference where corrosion problems are to be solved, and it is hoped that these remarks will prevent the young chemical engineer from spending his appropriation on materials that are more or less of an experimental nature instead of using products that have for many years given satisfactory service under similar conditions to those he has to meet.

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